Solar Fuels and Electricity by using Sunlight concentrating Systems

Christian Sattler
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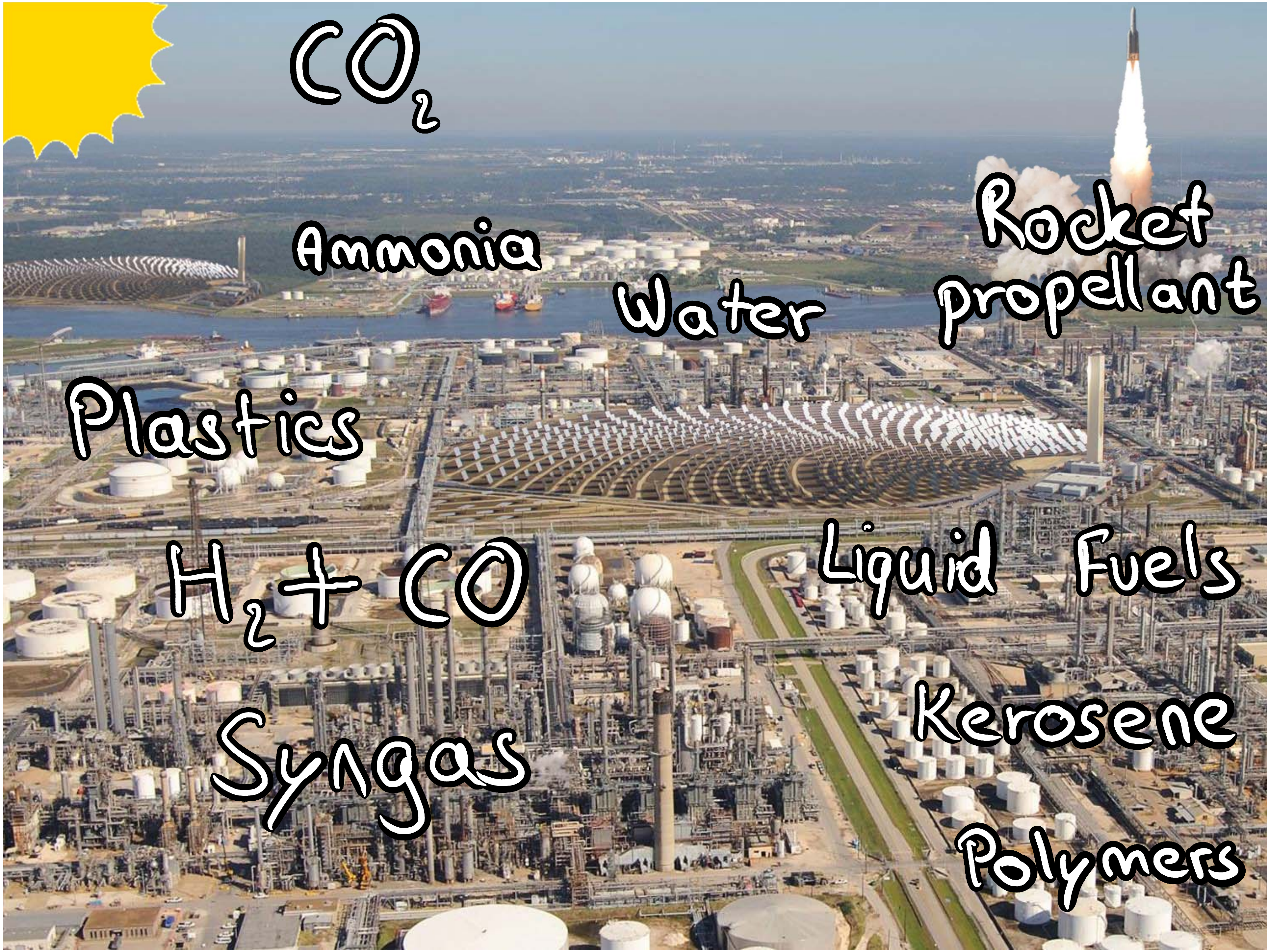
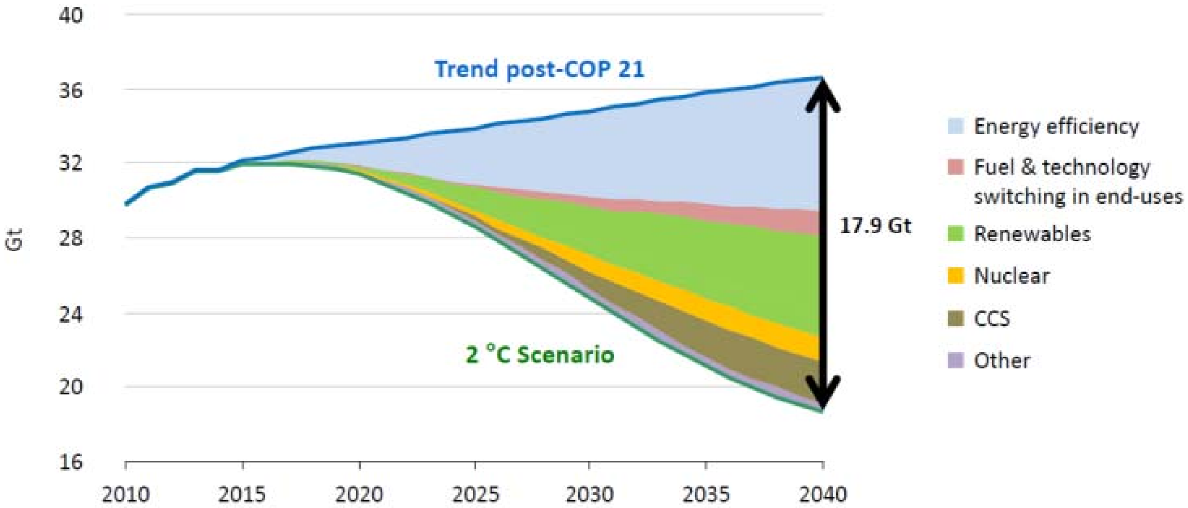
DLR



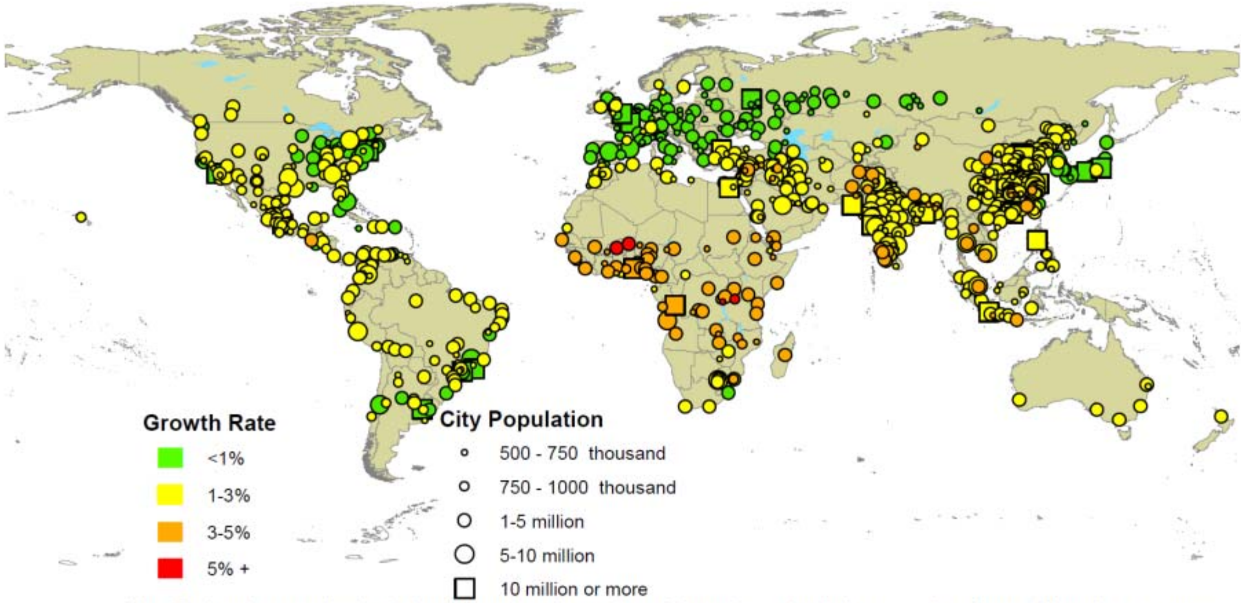
CO_2
Ammonia
Water
Rocket propellant
Plastics
$H_2 + CO$
Liquid Fuels
Syngas
Kerosene
Polymers

Global Challenges

- **Climat change**
- **Urbanization**
- **Ressources**
- **Markets**



Source: World Energy Outlook 2015



Note: Designations employed and the presentation of material on this map do not imply the expression of any opinion whatsoever on the part of the Secretariat of the United Nations concerning the legal status of any country, territory or area, or of its authorities, or concerning the delimitation of its frontiers or boundaries.

LABEL
PARIS2015
UN CLIMATE CHANGE CONFERENCE
COP21·CMP11

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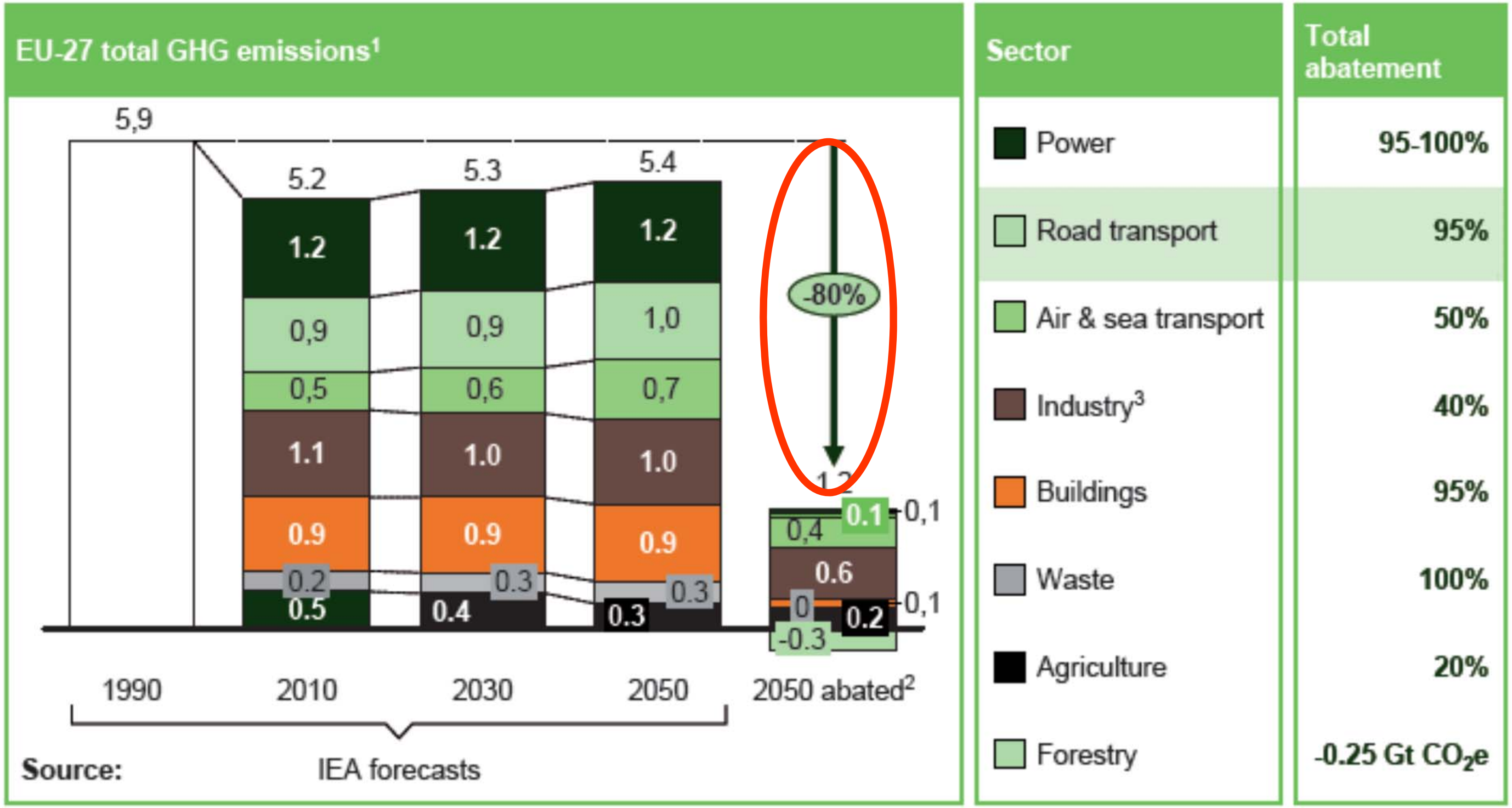
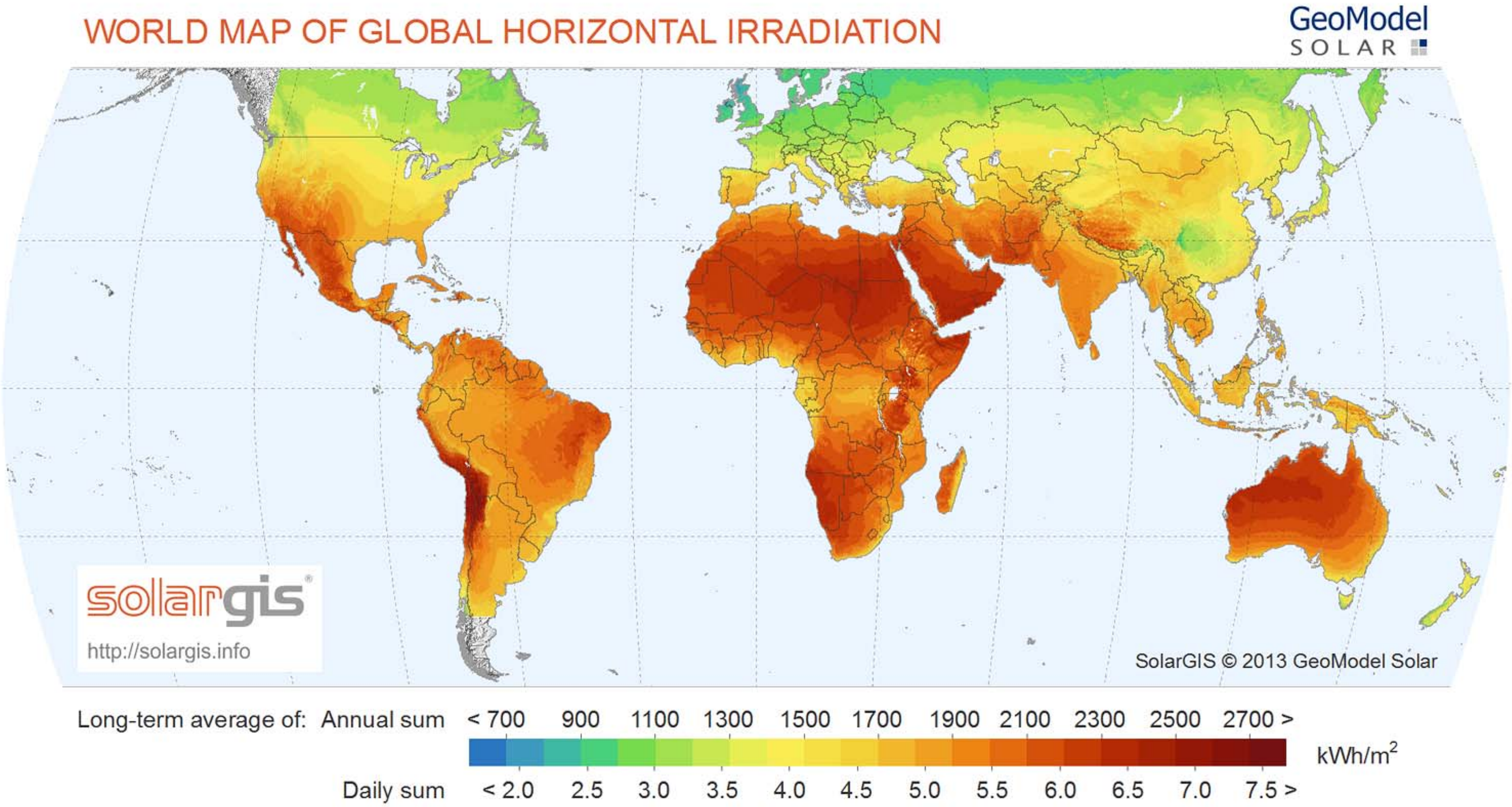
Development of EU GHG emissions [Gt CO_2e]



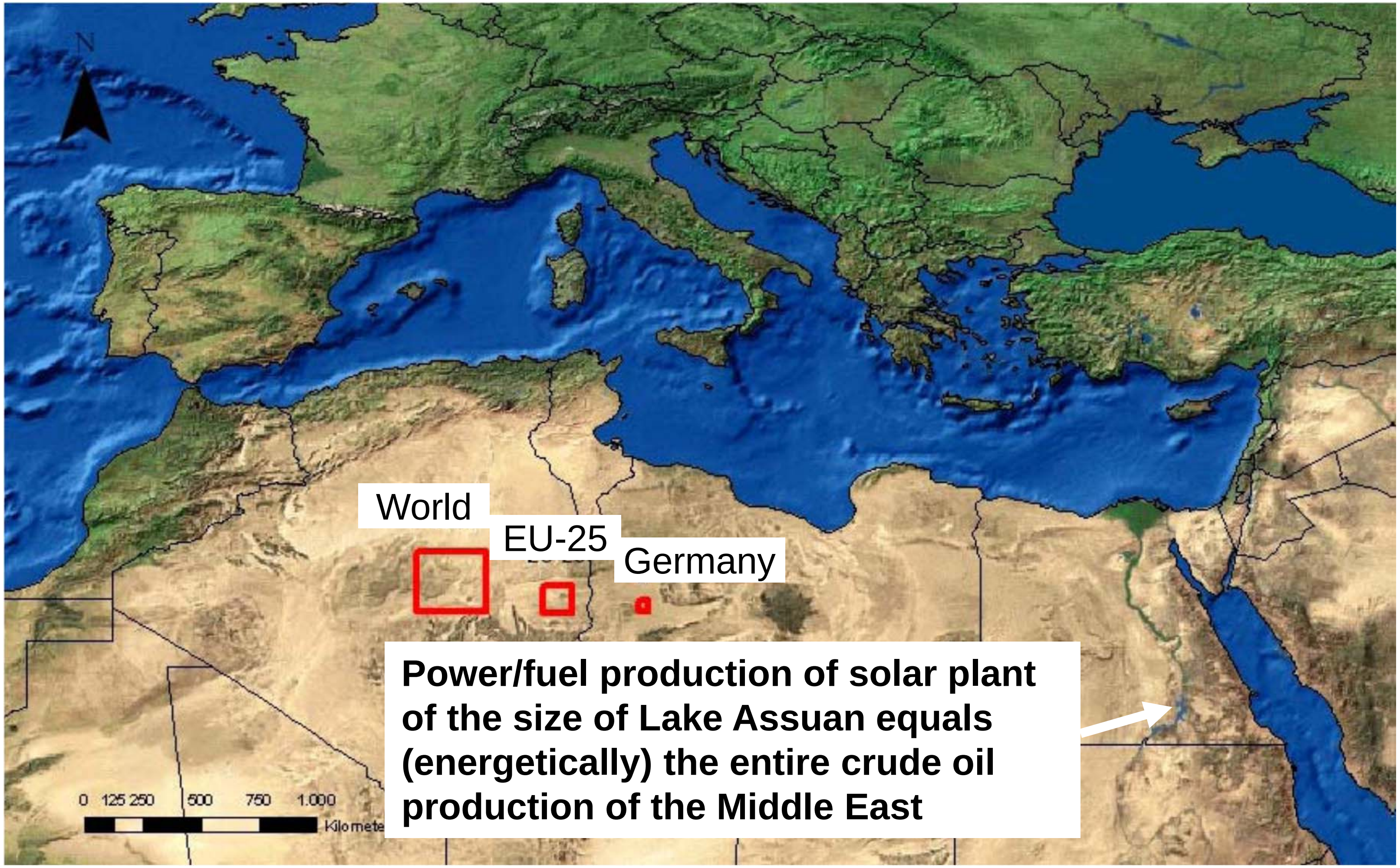
1 Large efficiency improvements are already included in the baseline based on the International Energy Agency, World Energy Outlook 2009, especially for industry
2 Abatement estimates within sector based on Global GHG Cost Curve
3 CCS applied to 50% of large industry (cement, chemistry, iron and steel, petroleum and gas, not applied to other industries)

SOURCE: www.roadmap2050.eu

Potential of Solar Energy



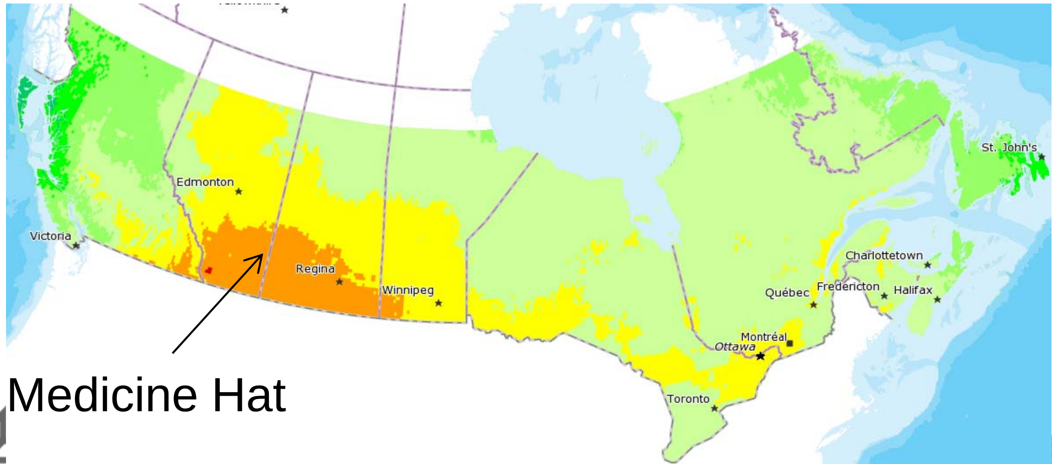
Potential of Solar Energy



Quelle: M. Schmitz, TSK Flagsol

CSP in Canada

- **1 MW_e Demonstration Plant**
  Medicine Hat, Alberta
- Integrated Solar Combined Cycle Demonstration plant 1 MW_e
- Combined with a local power plant 203 MW_e
- Location: 50.04° N; 110.72° W
  Frankfurt: 50.06° N; 8.40° O
- 2544 Sonnenstunden im Jahr
- DNI annual average 1833 kWh/m^2
- Annual production 4100 MWh_{th} = 1380 MWh_e



Medicine Hat

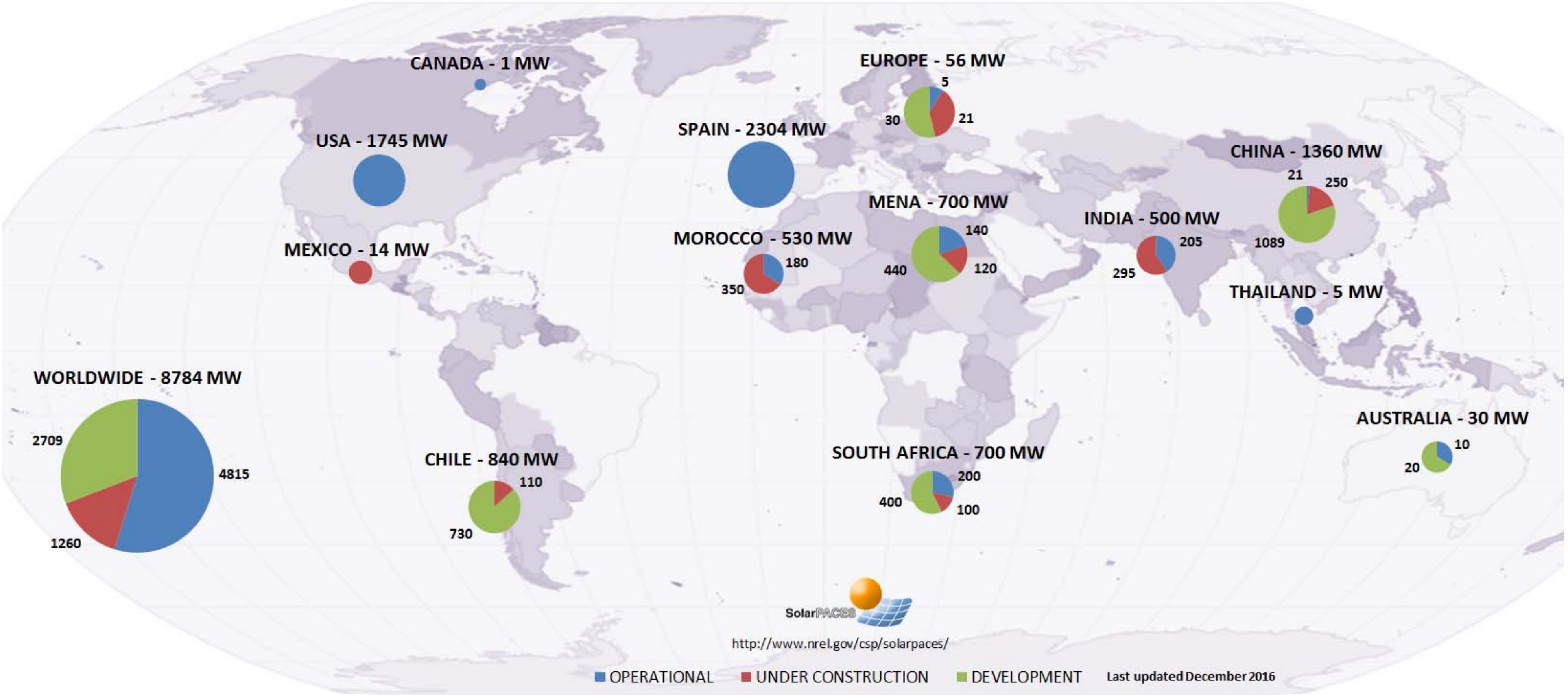
DNI annual average

700 - 900
901 - 1100
1101 - 1300
1301 - 1500
1501 - 1700
1701 - 1900
> 1900

Source: NRCAN/CANMET

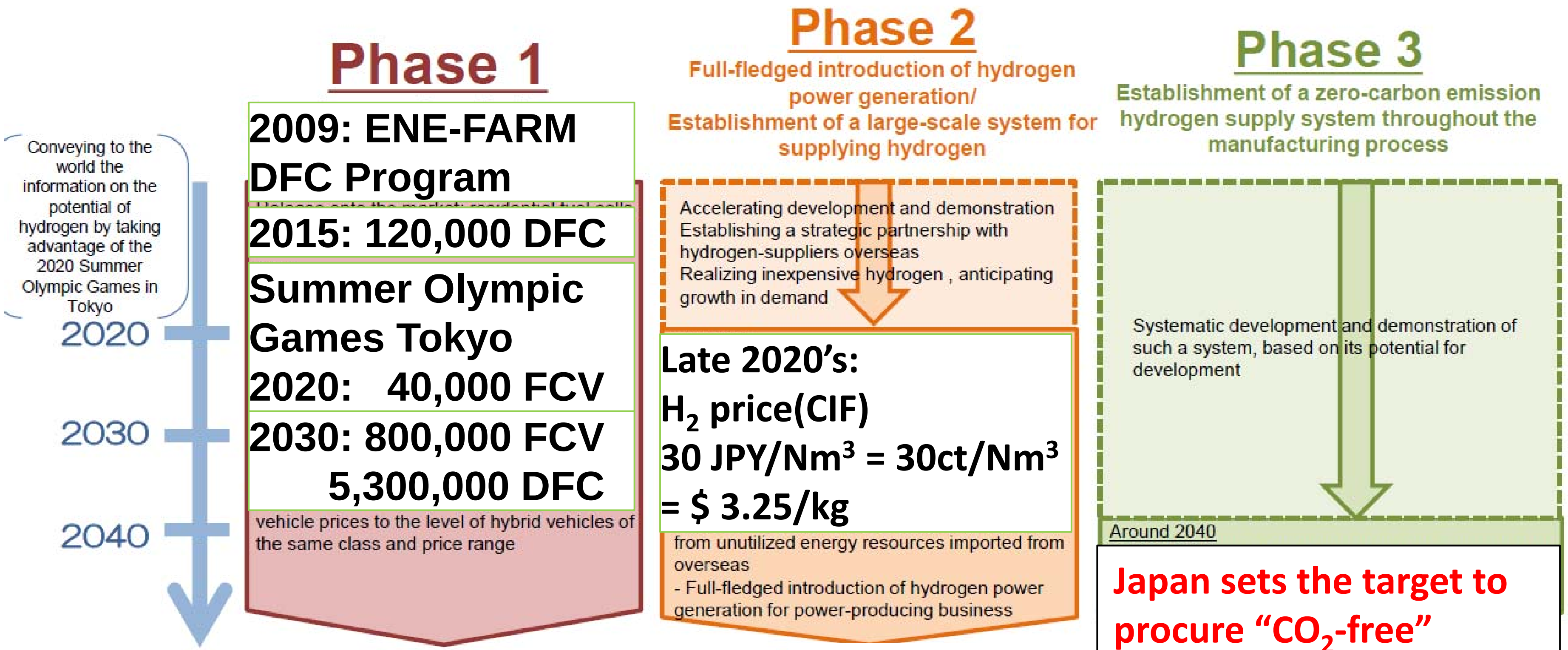
http://www.medicinehat.ca/index.aspx?page=1941

Global CSP Market



Japan‘s Strategic Roadmap towards a hydrogen society

(Agency for Natural Resources and Energy, METI, 2014, revised March 2016)



Japan sets the target to procure “CO_2-free” hydrogen in 2040 and looks for clean and cost competitive hydrogen globally.

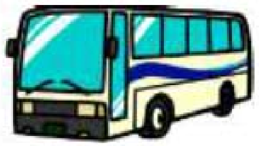
DFC: Domestic Fuel Cell
FCV: Fuel Cell Vehicle
CIF : Cost, Insurance, Freight

Annual Hydrogen Consumption (per unit)

(Source: METI, Japan)

FCV
94 kg/yr

(H_2-type)
residential FC
201 kg/yr



FC Bus
4,600 kg/yr

1GW H_2 power plant
(100% H_2 fuel)
200,000~400,000 ton/yr

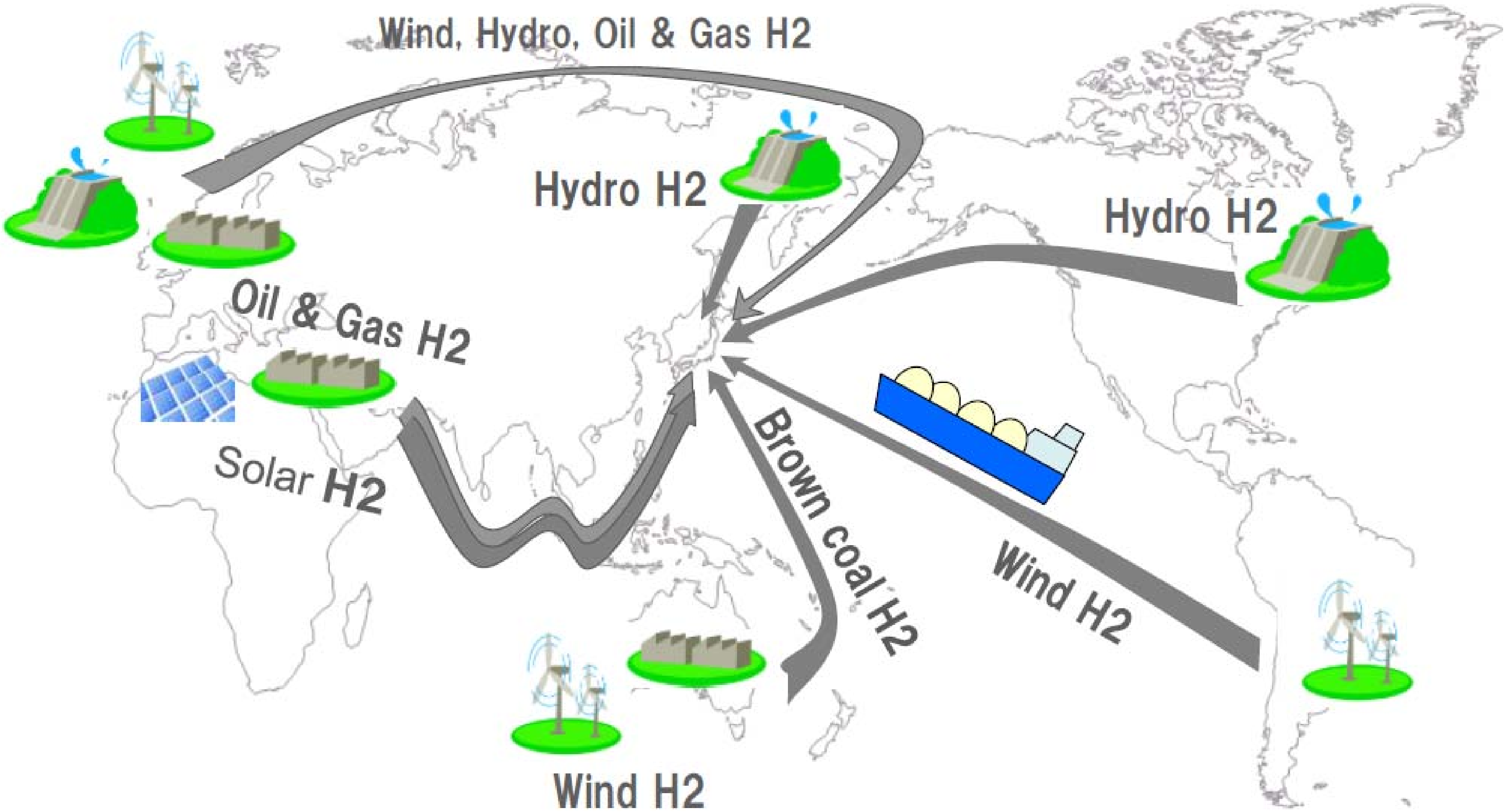
= 2~4 million FCVs

Japanese energy mix 2013: 303 GWe,

- 44 GWe nuclear, 45 GWe hydro,
- 36 GWe coal, 47 GWe gas,
- 41 GWe oil, 18 GWe oil or coal,
- 51 GWe autoproducers' 'combustible fuels' 13 GWe solar
- 2.6 GWe wind 0.5 GWe geothermal.

(Source: IEA, 2014)

Kawasaki Vision – Hydrogen Potential from Overseas



Kawasaki vision for the cryogenic liquid hydrogen market – team-up with Shell (March 15, 2016)

川崎重工業株式会社

川崎重工グループは、国内で有数の大型水素貯蔵タンクや水素運搬車を製造している技術と経験を活かし、未来社会に向けての新しいエネルギー構想として「CO_2フリー水素コンセプト」を提案しています。

http://global.kawasaki.com/en/stories/hydrogen/

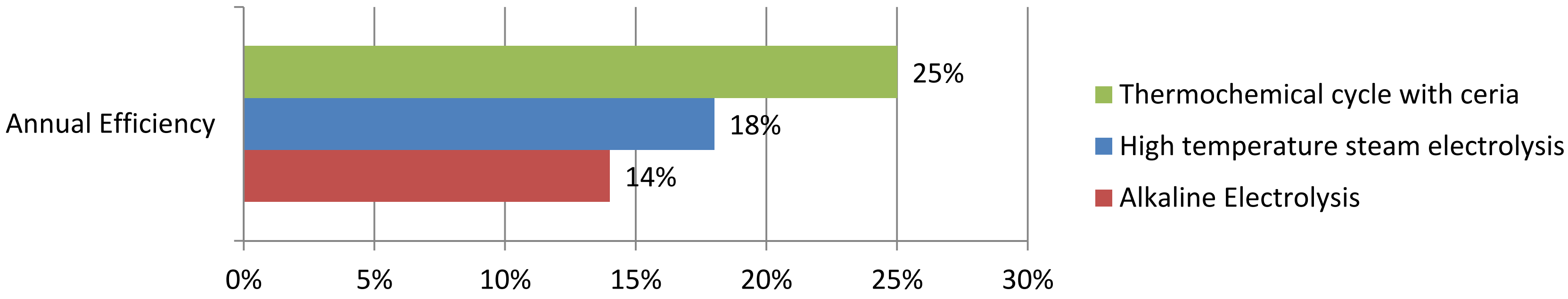
Technical Challenges – High temperatures and constant conditions
Promising and well researched Thermochemical Cycles

	Steps	Maximum Temperature (°C)	LHV Efficiency (%)
Sulphur Cycles			
Hybrid Sulphur (Westinghouse, ISPRA Mark 11)	2	900 (1150 without catalyst)	43
Sulphur Iodine (General Atomics, ISPRA Mark 16)	3	900 (1150 without catalyst)	38
Volatile Metal Oxide Cycles			
Zinc/Zinc Oxide	2	1800	45
Hybrid Cadmium		1600	42
Non-volatile Metal Oxide Cycles			
Iron Oxide	2	2200	42
Cerium Oxide	2	2000	68
Ferrites	2	1100 – 1800	43
Low-Temperature Cycles			
Hybrid Copper Chlorine	4	530	39

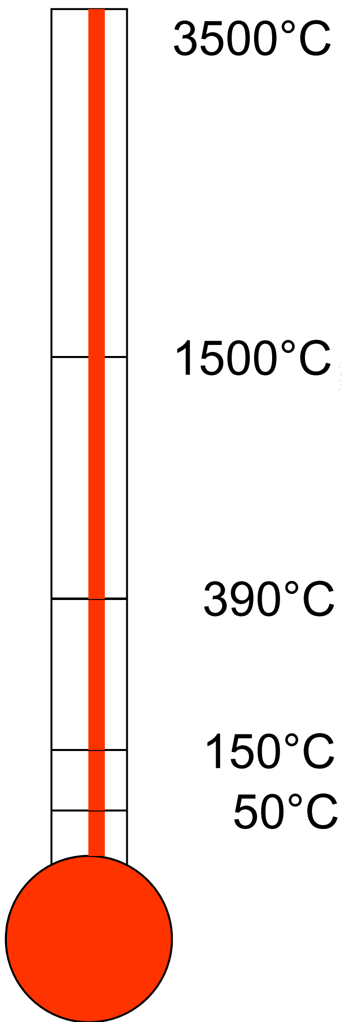
Solar Hydrogen by Water Splitting: Efficiency Comparison vs. Benchmark

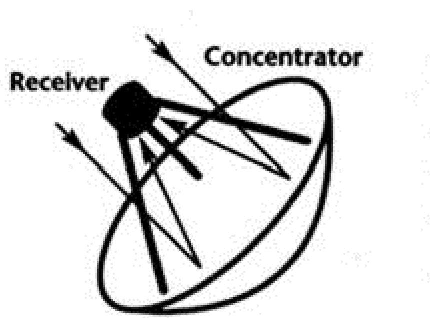
Process	temperature of the chemical reaction	Solar interface receiver temperature
Alkaline Electrolysis	25°C	Solar PV
High temperature steam electrolysis	850°C	Future solar tower 1200°C
Thermochemical cycle with ceria	1500 / 1150°C	Future solar dish 1500°C

*G.J. Kolb, R.B. Diver SAND 2008-1900 / N. Siegel et al. I&EC Research May 2013

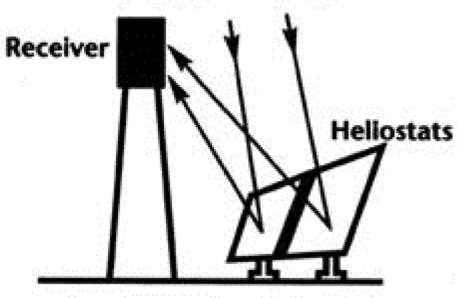


Temperature Levels of Solar Concentrators

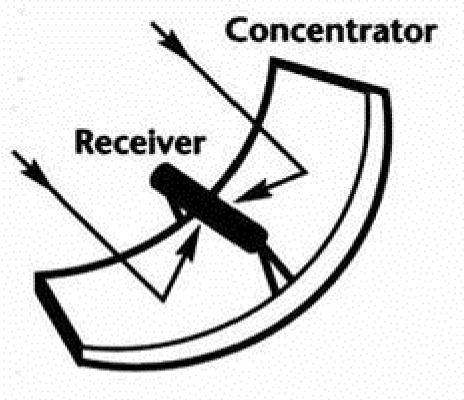




Paraboloid „Dish“
Concentration < 10.000
Power < 500 kW_{th}



Solar Tower
(Central Receiver System)
Concentration >100
Power >100 MW_{th}



Parabolic Trough /
Linear Fresnel
Concentration 10 - 100
Power 10 - >100 MW_{th}

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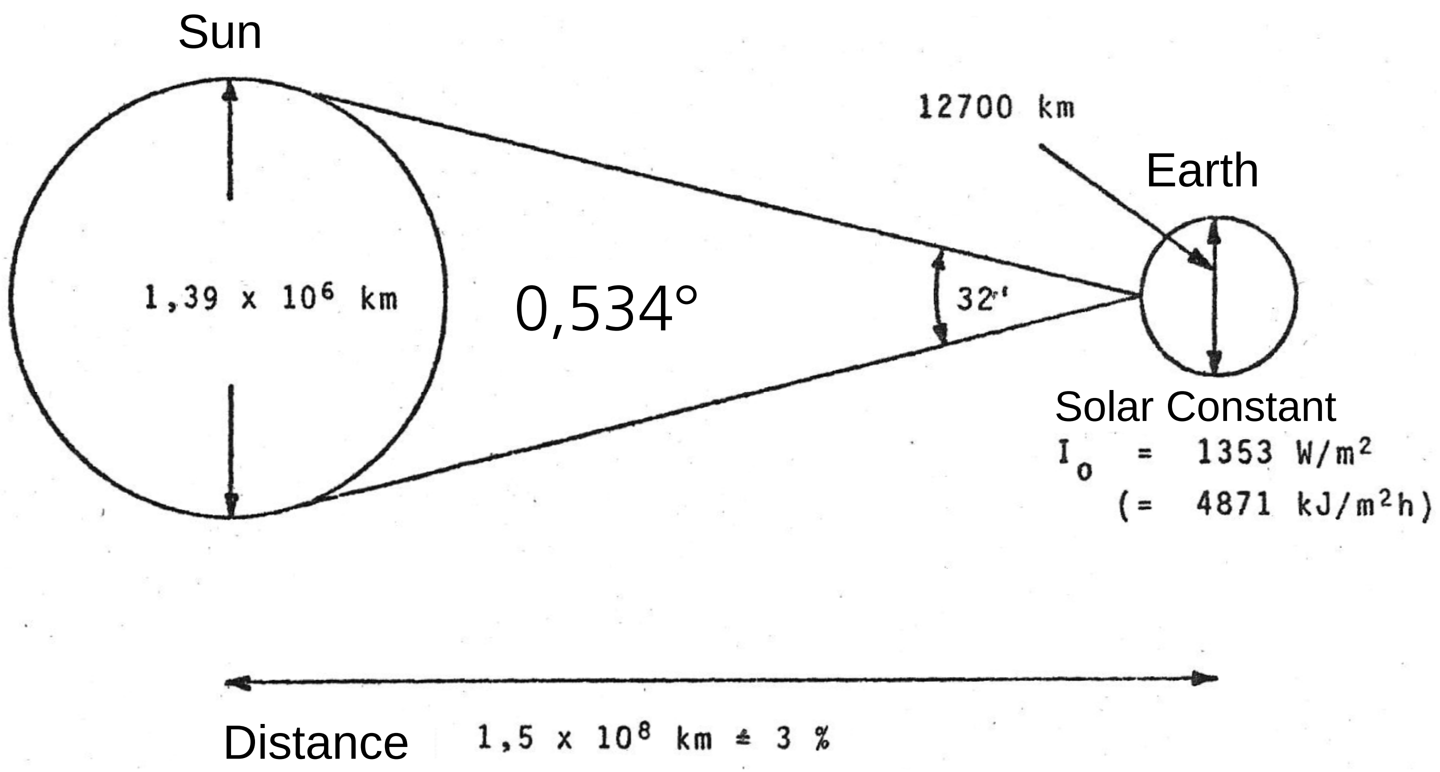
Maximum Concentration of Solar Radiation on Earth



$$C_{\max,3D} = \frac{A}{A'} = \frac{\sin^2 90°}{\sin^2 0{,}267°} \approx 46200 \qquad C_{\max,2D} = \frac{A}{A'} = \frac{\sin 90°}{\sin 0{,}267°} \approx \sqrt{46200} = 215$$

$$\boxed{C_{max} = 46200 \cdot 0.5 \cdot 0.5 = 11550}$$

$$\boxed{C_{max} = 215 \cdot \frac{1}{\sqrt{2}} \cdot \frac{1}{\sqrt{2}} = 107.5}$$

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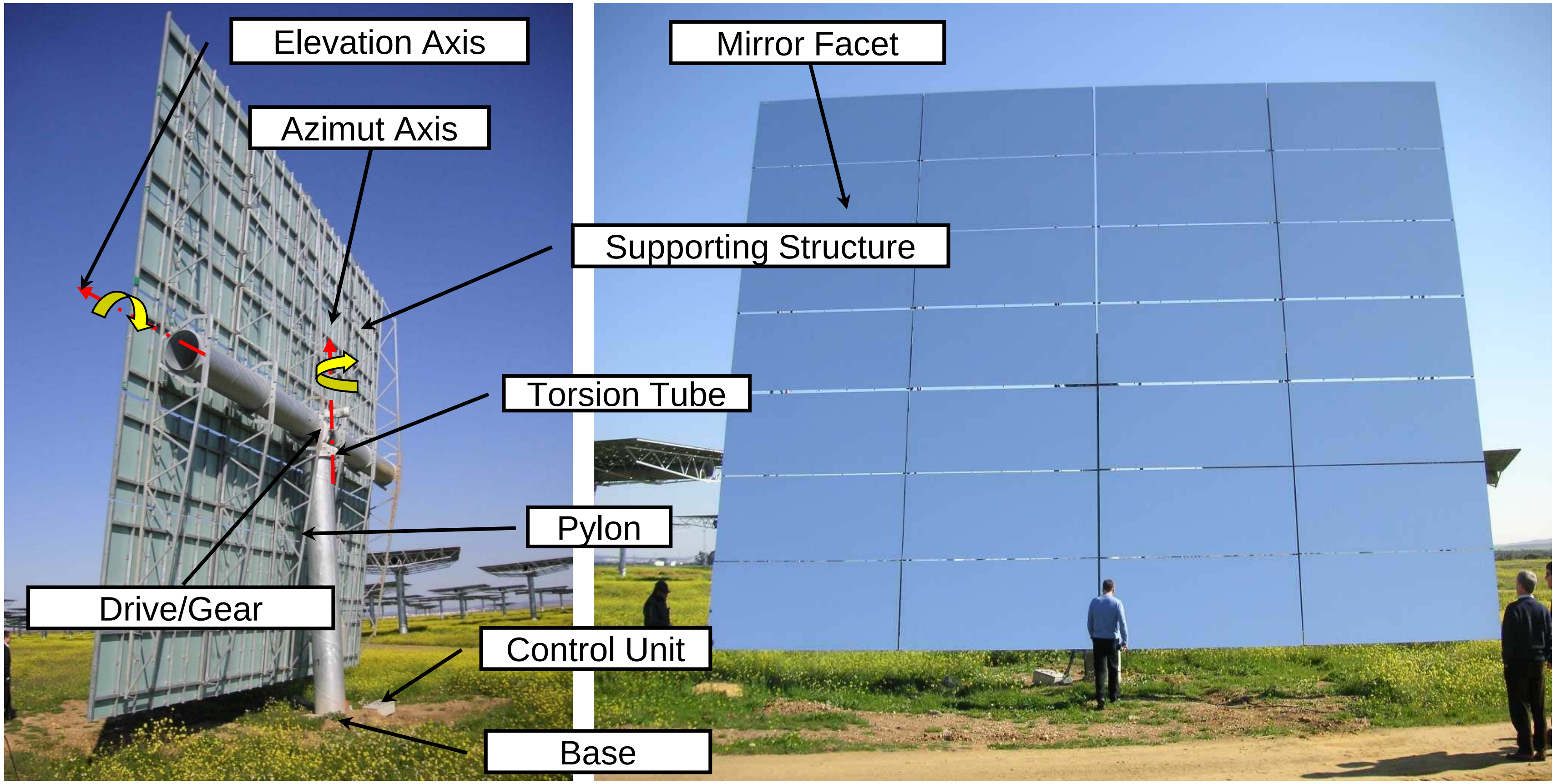
Heliostat

- Components



Sanlucar (120 m²), Abengoa Solar S.A.

Heliostat Facets

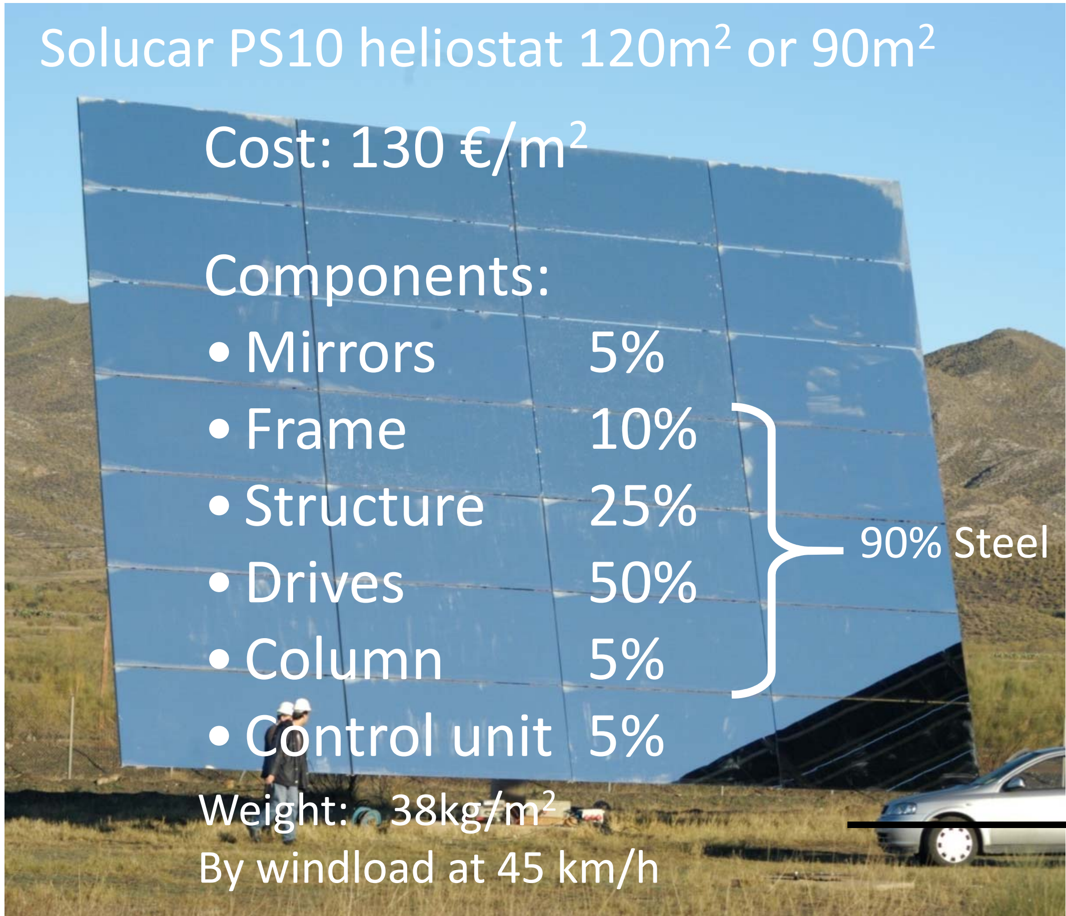
Heliostat with rectangular mirror facets

Metal foil heliostat with round facets

Steinmüller 150 m² Heliostat

Heliostat Cost

Cost reduction potential



Solucar PS10 heliostat 120m² or 90m²

Cost: 130 €/m²

Components:

- Mirrors 5%
- Frame 10%
- Structure 25%
- Drives 50%
- Column 5%
- Control unit 5%

90% Steel

Weight: 38kg/m²

By windload at 45 km/h

Steel min.
2 €/kg

Minimum cost
70 €/m²

Maximum
Cost reduction
46%

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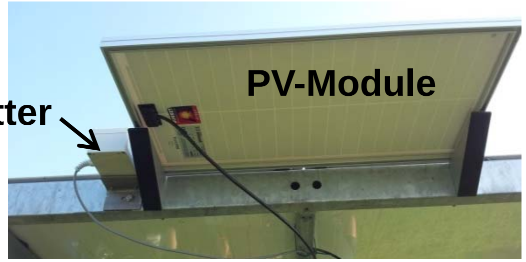
Heliostat Control

- Standard
  - Control and energy supply by wire
  - Excavation necessary

- Autonomous
  - Radio control
  - Energy supply by PV-Module
  - Capacitor storage



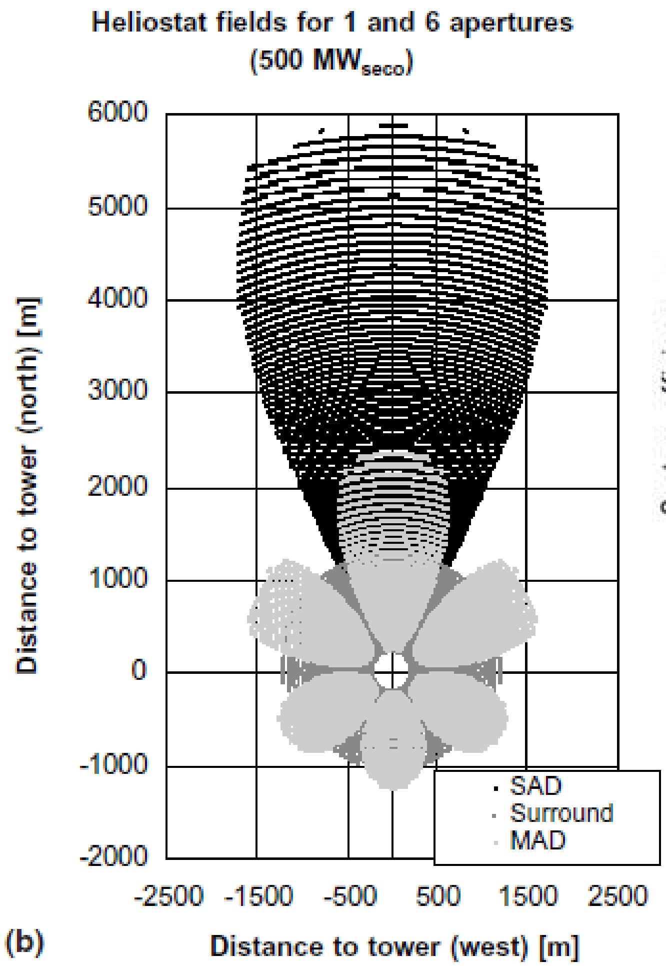
http://autor.trinamic.com/heliomesh-project/

HELIOMESH

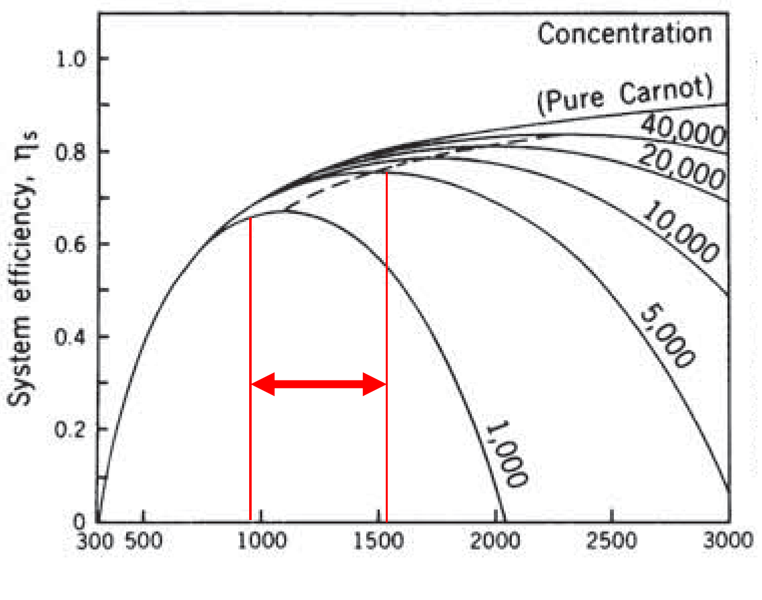
Solar Field Development

Solar fields need to fit the requirements of the process

- Availability
- Concentration
- Secondary optics
- Location



M. Schmitz et al., Solar Energy 80 (2006) 111–120.

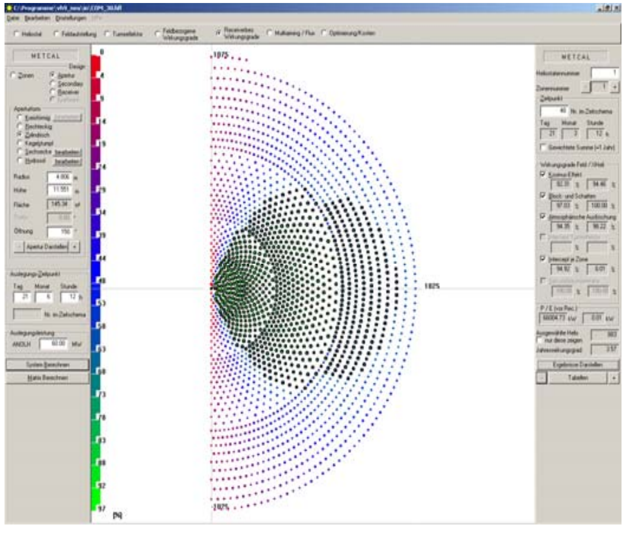


E.A. Fletcher, R.L. Moen, Science, 197 (1977) 1050-1056.

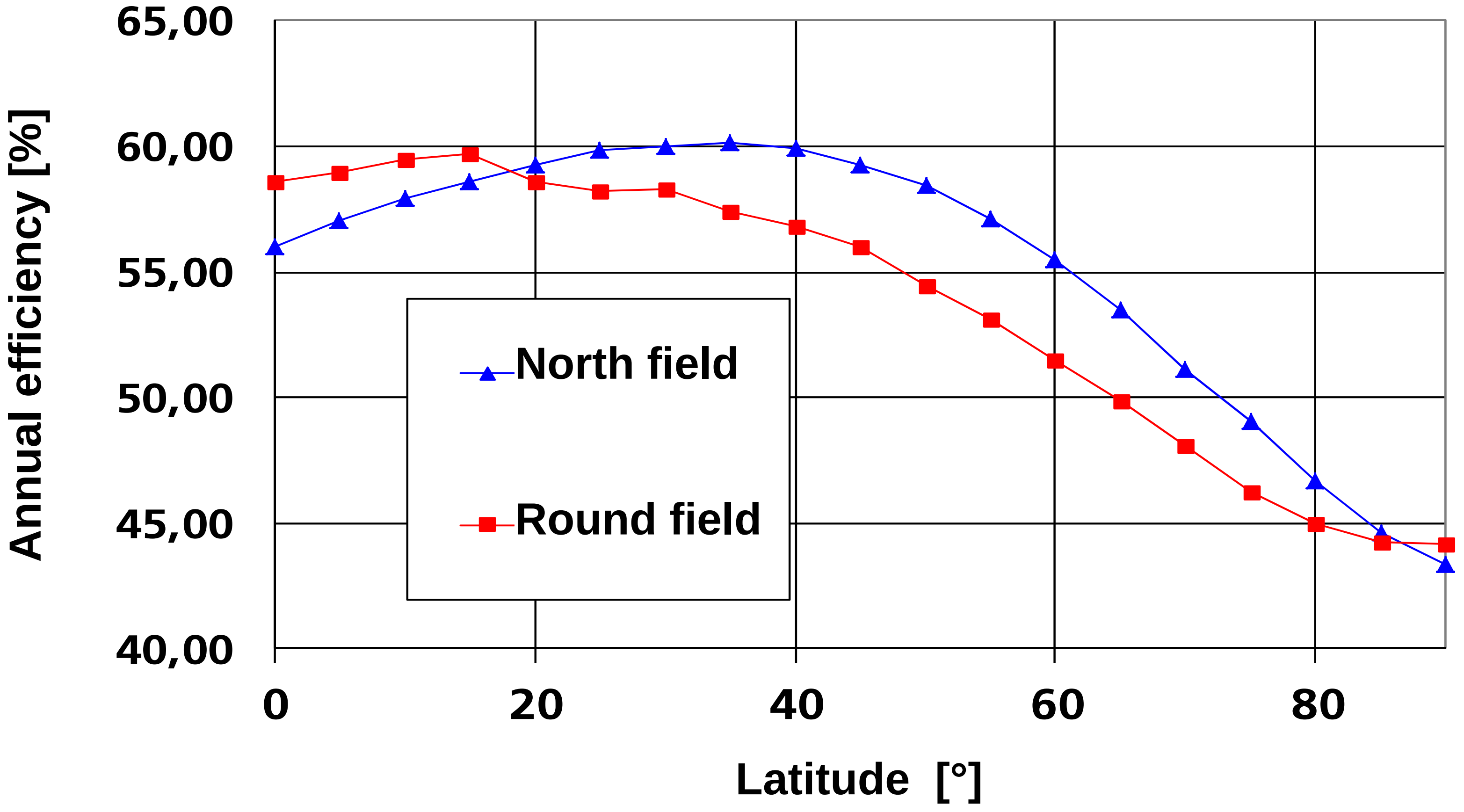
Heliostat Field Design

- Field Design
  - Dimensioning of the solar field
  - Choice, number, and positioning of the heliostats
  - Mirror quality and field design are decisve for the efficiency and the cost
- Field Optimization
  - Position of the heliostats,
  - Tower hight
  - Receiver size
- Optimization tools are avaliable (e.g. HFLCAL)

PS10: Abengoa Solar



Heliostat Fields: Efficiency depends on Location

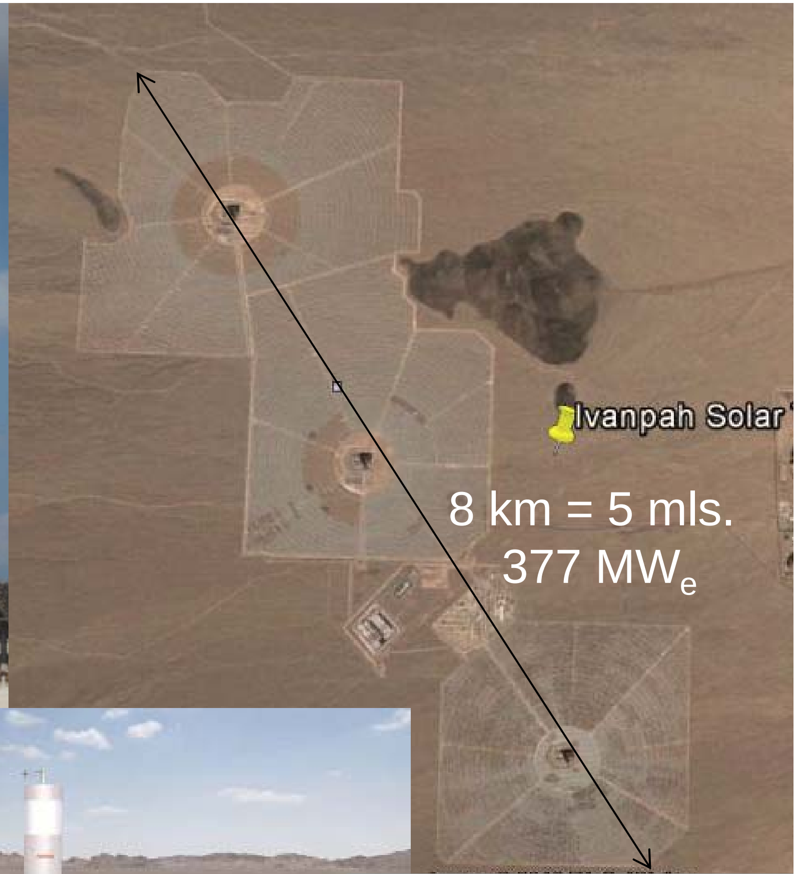


Heliostat field Layouts

North fields, Abengoa Solar, 37°N
Sanlucar la Mayor, Spain

Round field, SolarReserve, 38°N
Crescent Dunes, Tonopah, NV, USA

Solar Towers



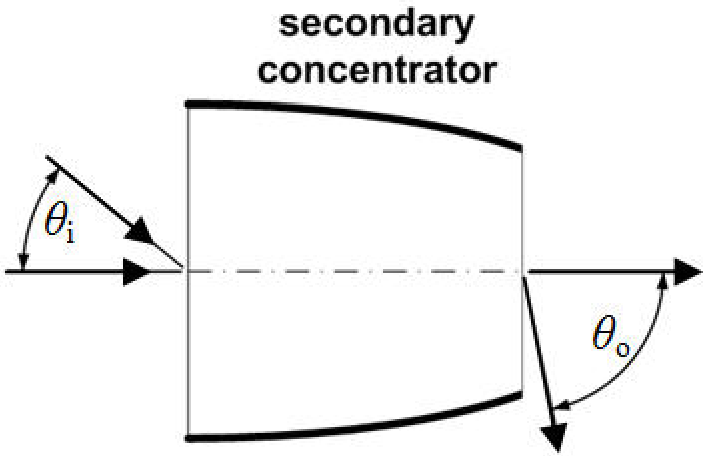
On the Web:

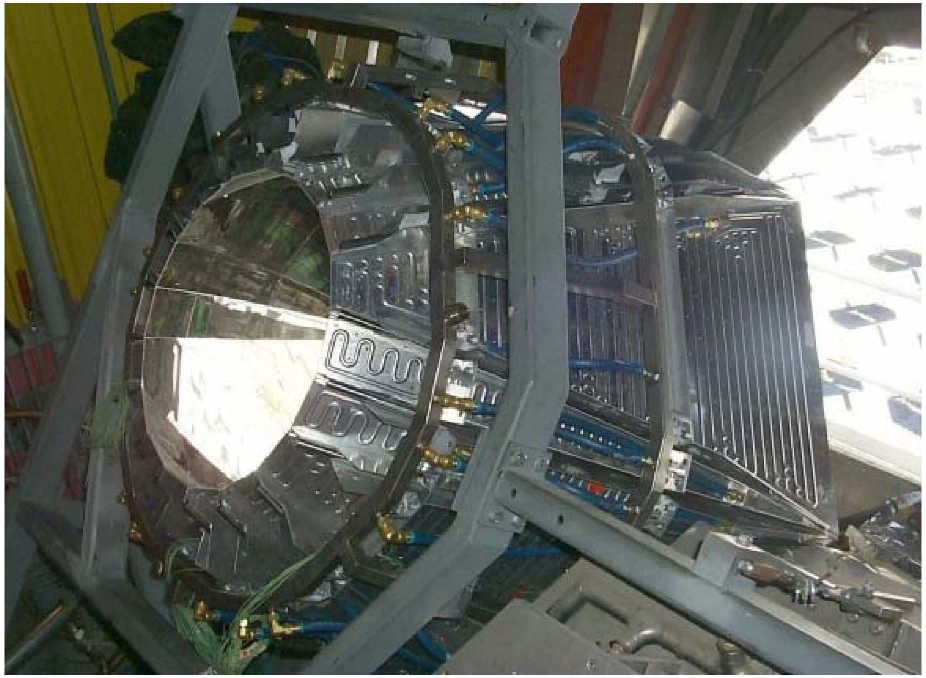
http://www.ivanpahsolar.com/
http://www.torresolenergy.com/TORRESOL/home/en
http://www.solarreserve.com/en/global-projects/csp/crescent-dunes
http://www.abengoasolar.com/web/en/

Secondary Concentrators

Diameter of a heliostat field focus is several meters

To increase the concentration and reduce the aperture area secondary morror optics are used



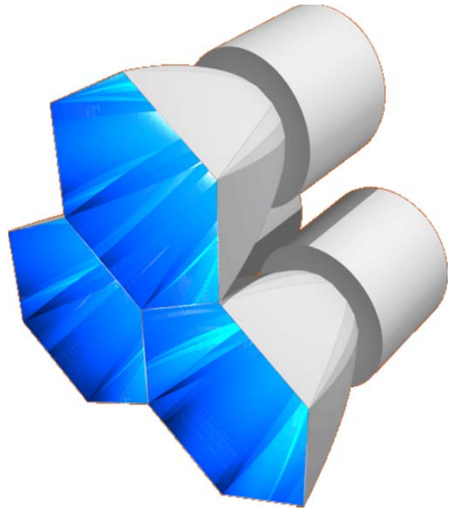


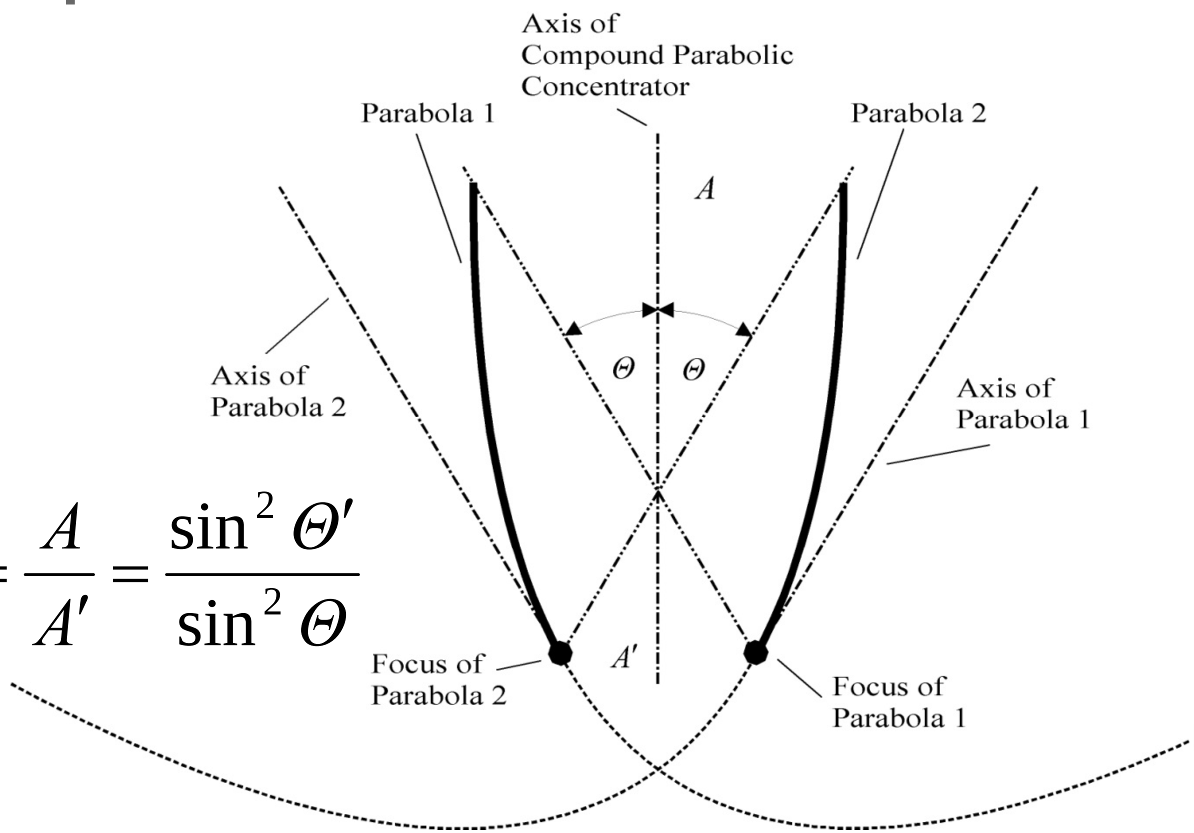
REFOS Secondary concentrator

CESA-I Tower
Plataforma Solar de Almería, Spain

Absorption losses ca. 8-12%
Efficiency 75 – 90 %
Aperture area reduction 4-5 times

Compound Parabolic Concentrator

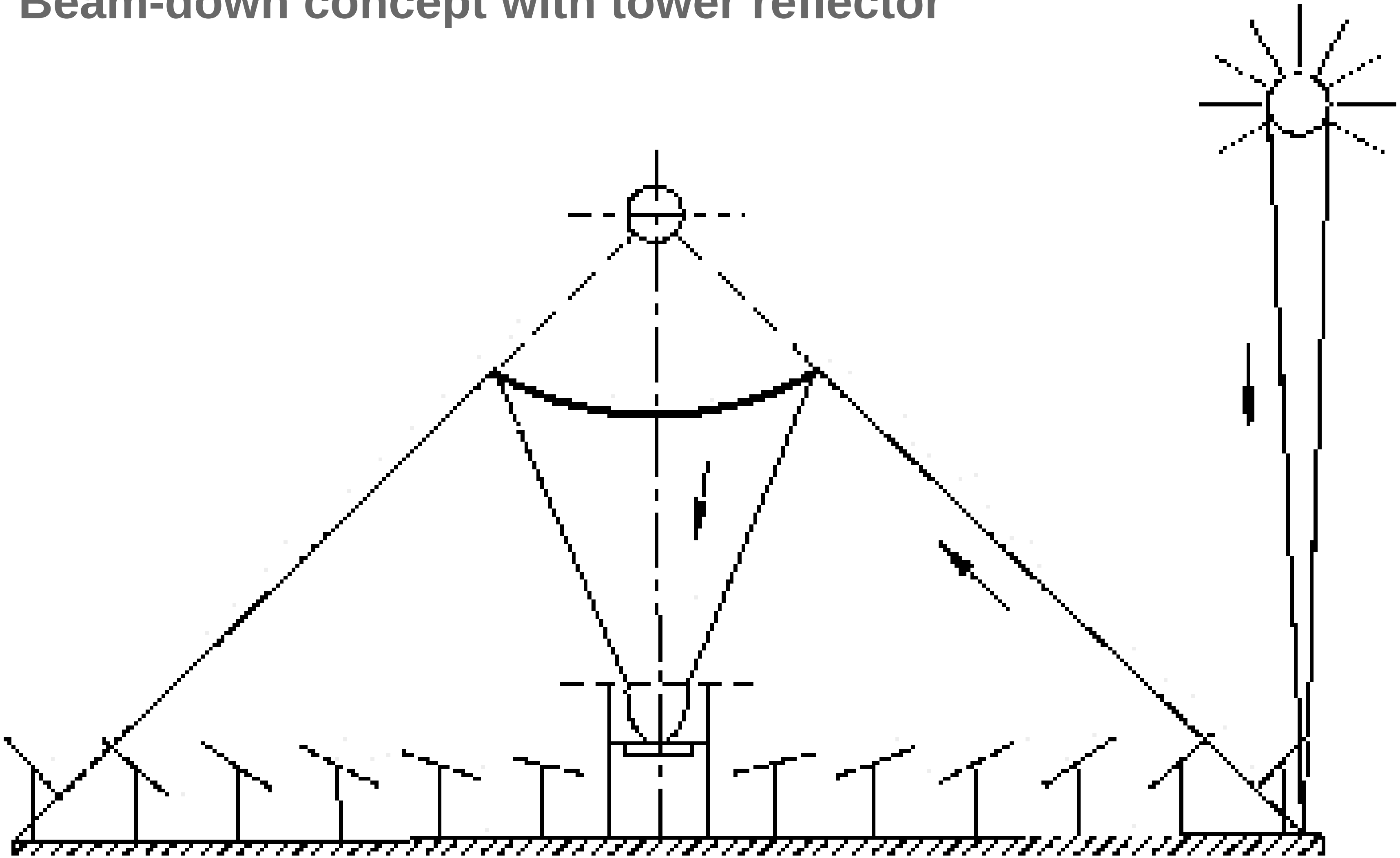




$$C_{3D} = \frac{A}{A'} = \frac{\sin^2 \Theta'}{\sin^2 \Theta}$$

Radiation acceptance angle $$\Theta = \arcsin\sqrt{\frac{A'}{A}}$$

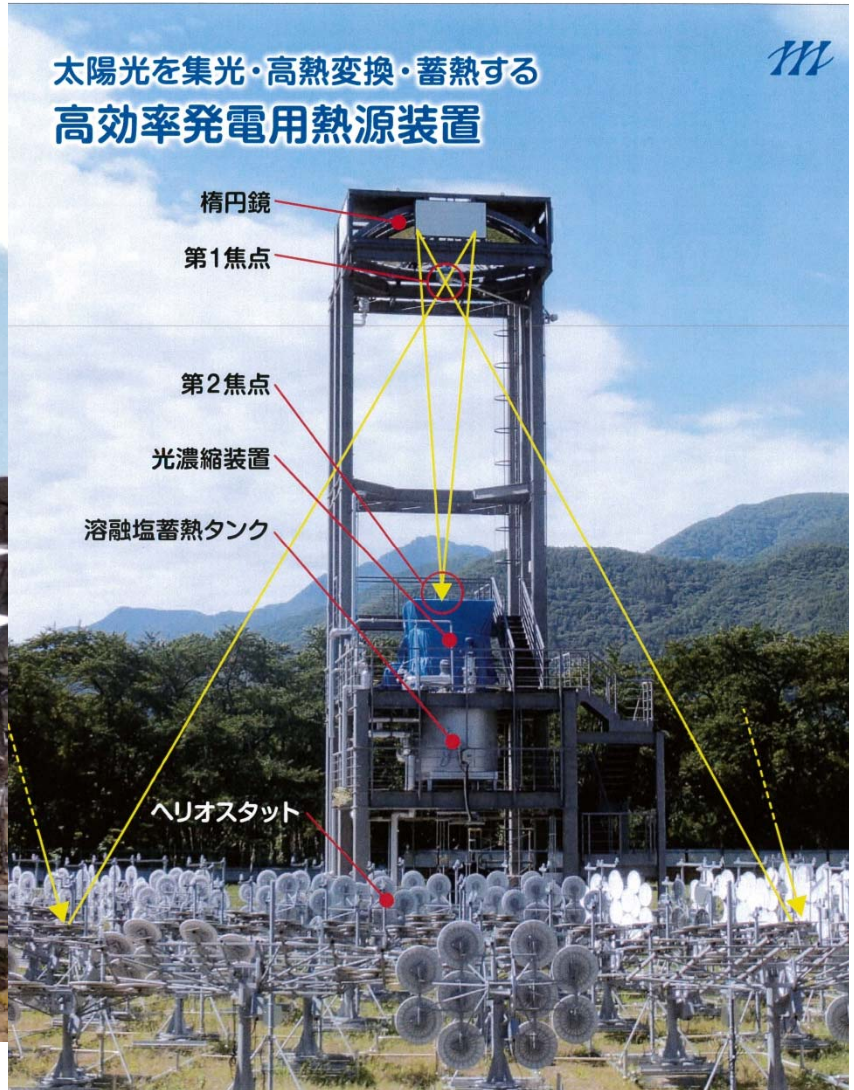
Secoundary Concentrators
Beam-down concept with tower reflector



Beam-down with tower reflector, Weizmann Institute of Science, Rehovot, Israel

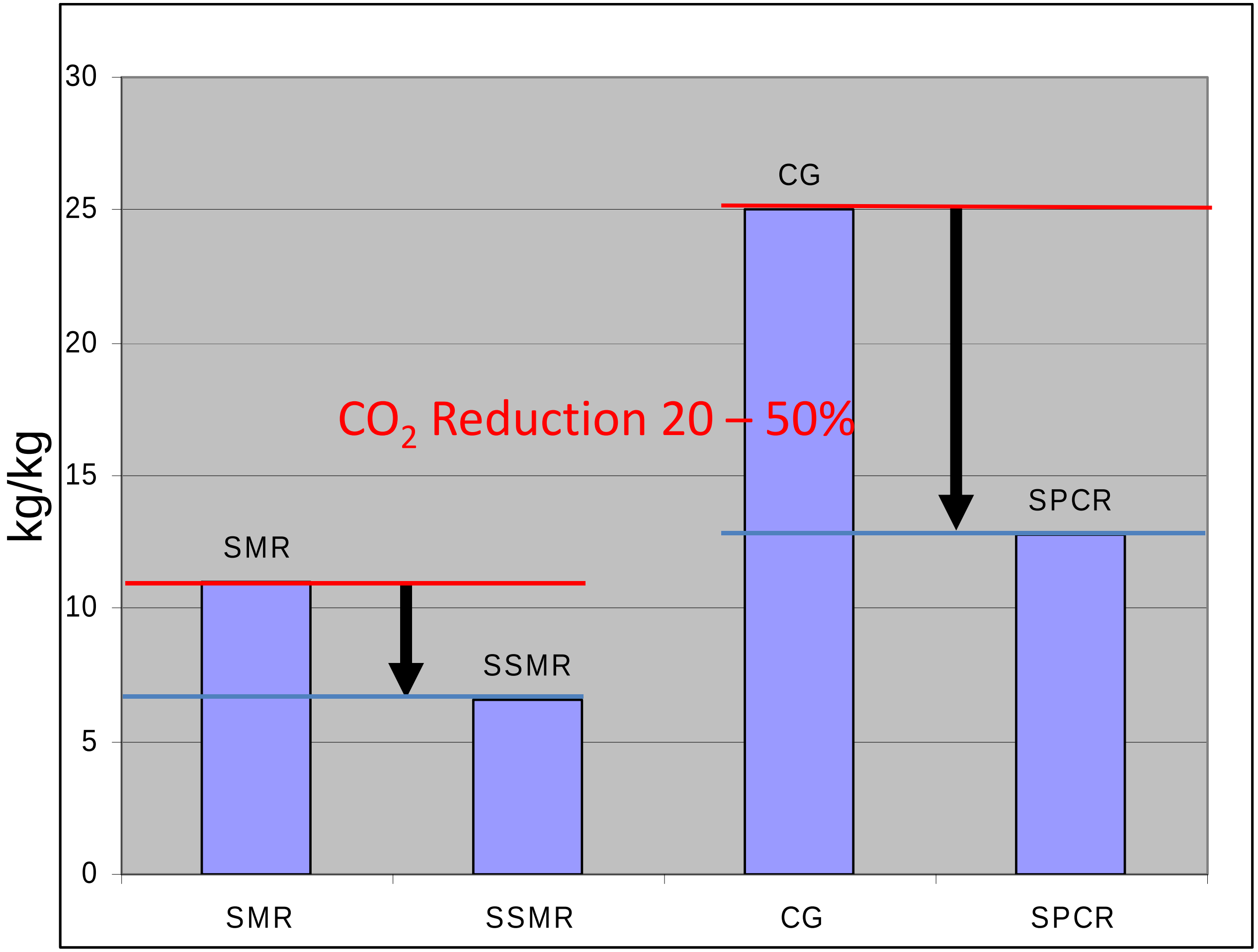
Beam-down with tower reflector, Weizmann Institute of Science, Rehovot, Israel

Beam-down with tower reflector, Mitaka Khoki, Nagano, Japan

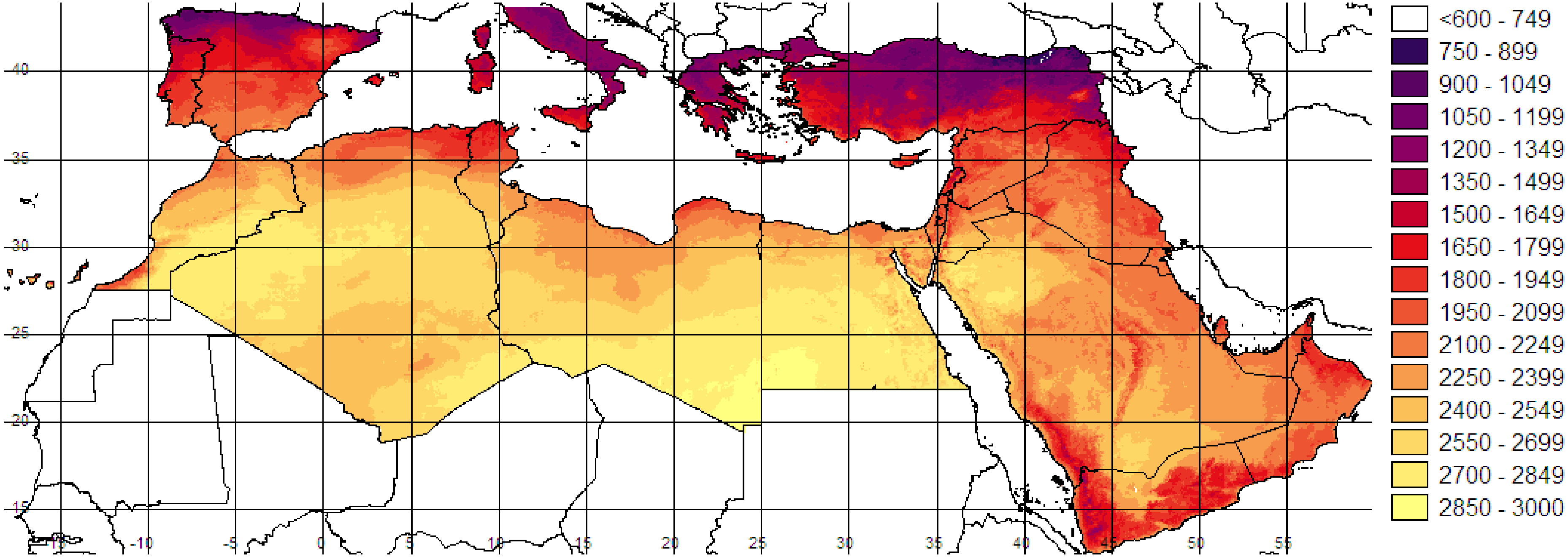


Beam-down with tower reflector, Mitaka Khoki, Nagano, Japan

CO_2 Reduction by solar heating of state of the art processes like steam methane reforming and coal gasification T = 650 – 1000°C



Atlas of Annual Direct Normal Irradiance



DNI 2002 in kWh/m²/y

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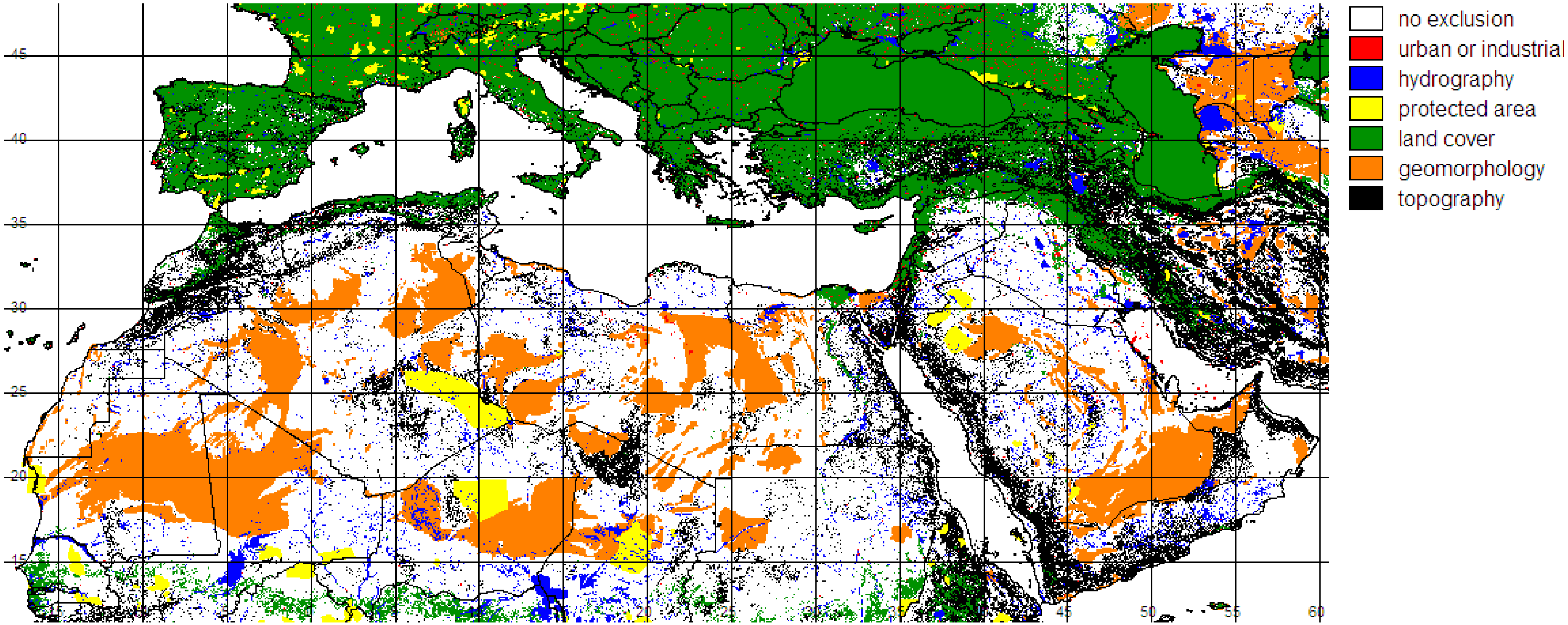
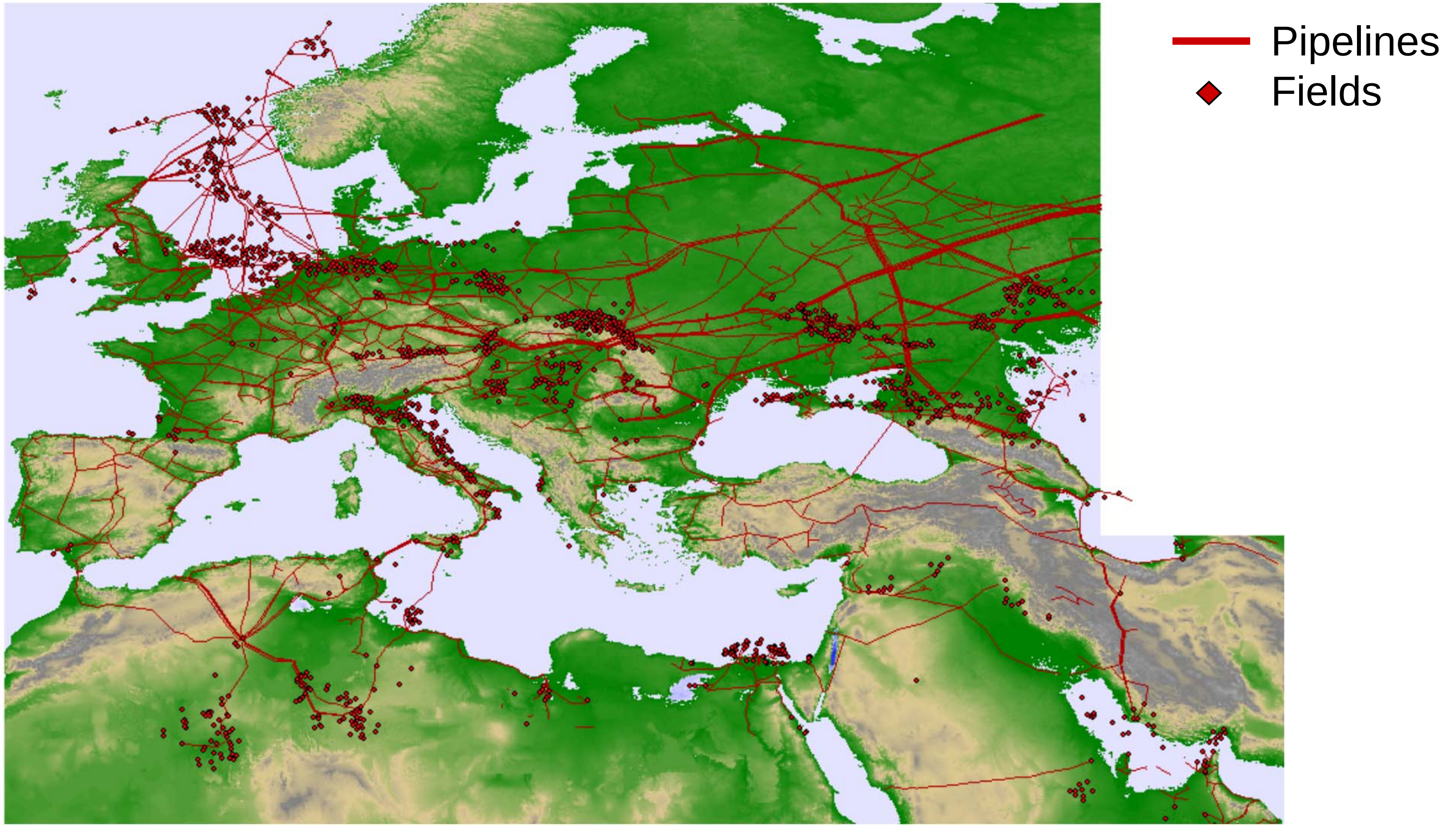
Atlas of Exclusion Areas



Atlas of Natural Gas Pipelines and Gas Fields



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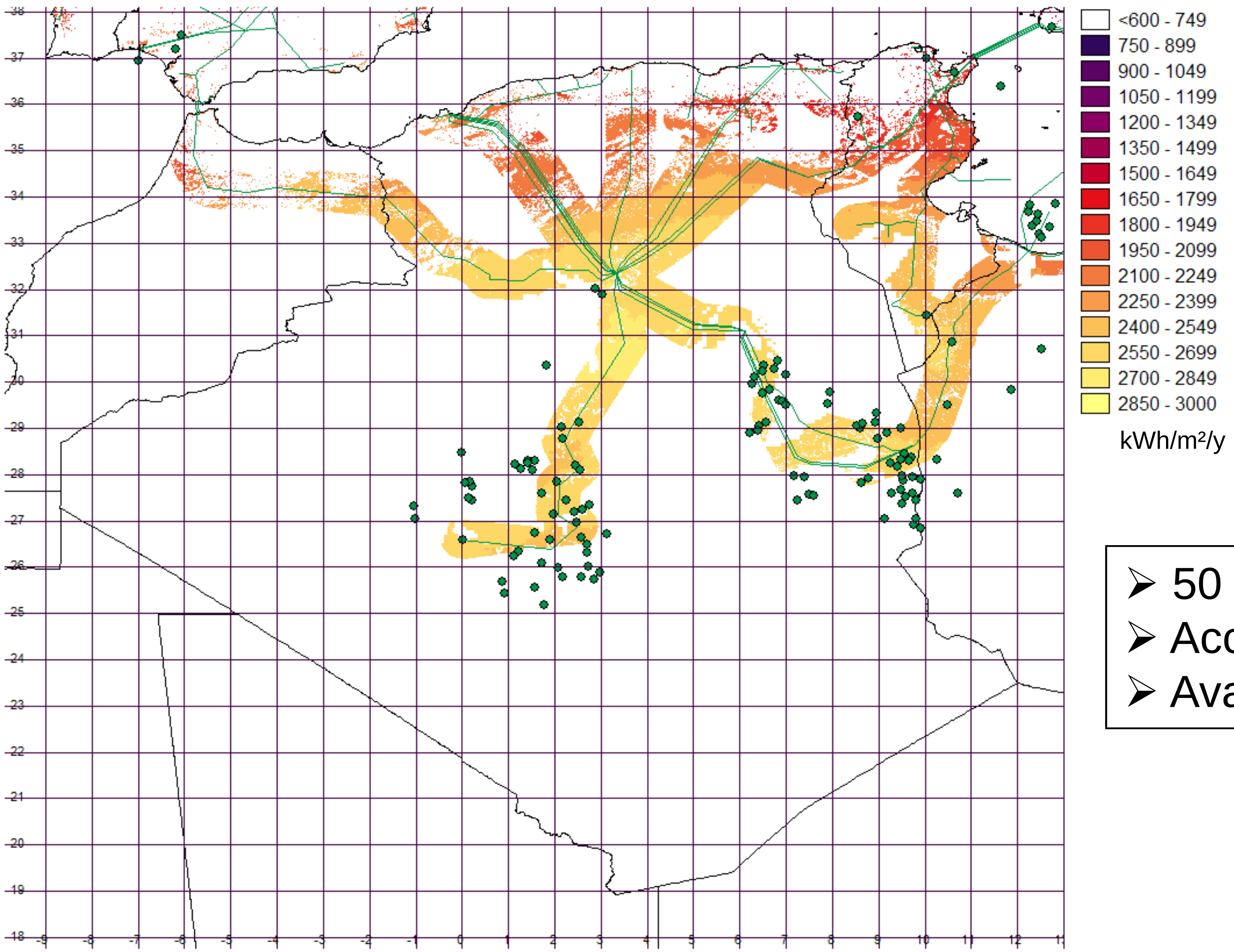
Overlay of Data Sets for Algeria

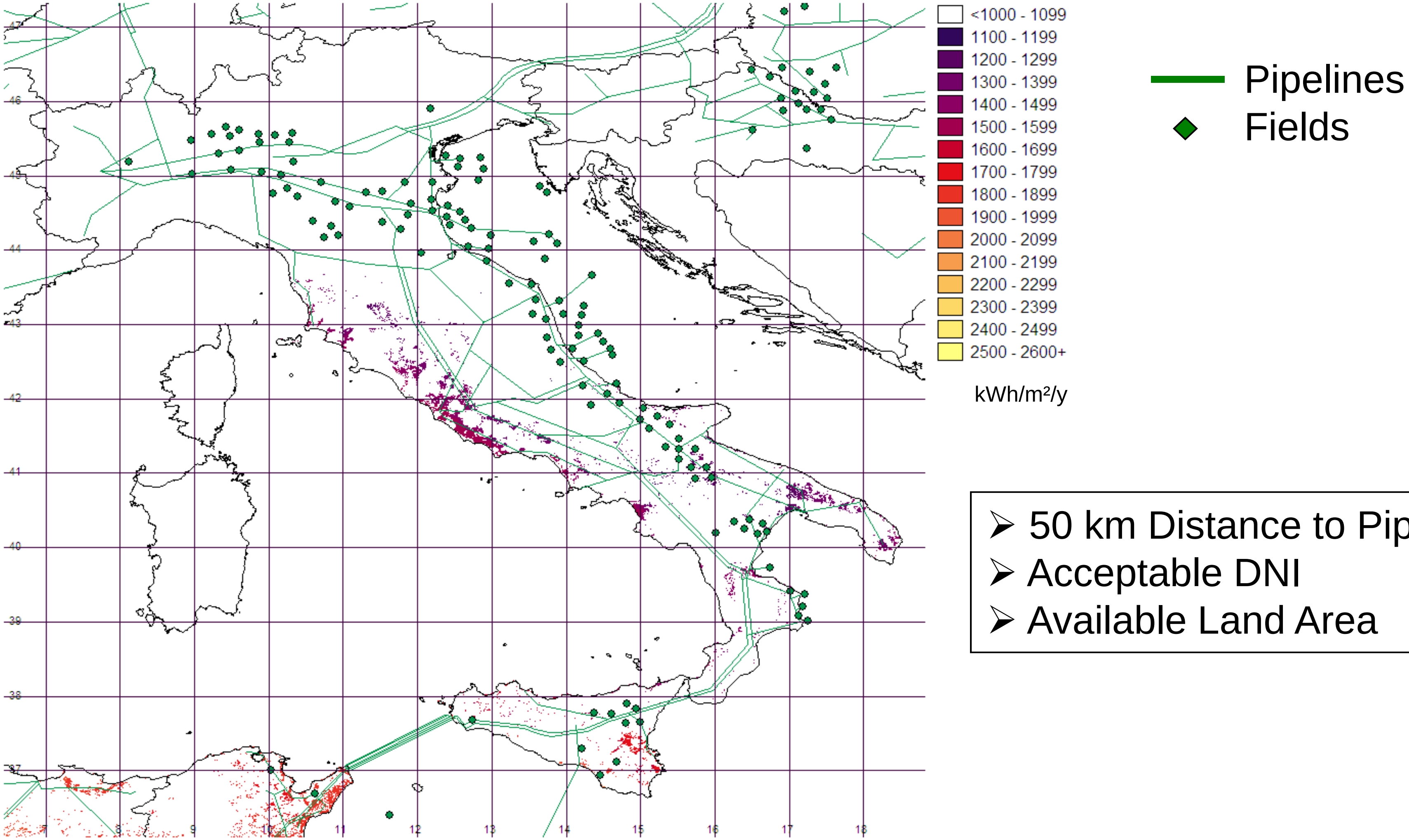


Pipelines

Fields

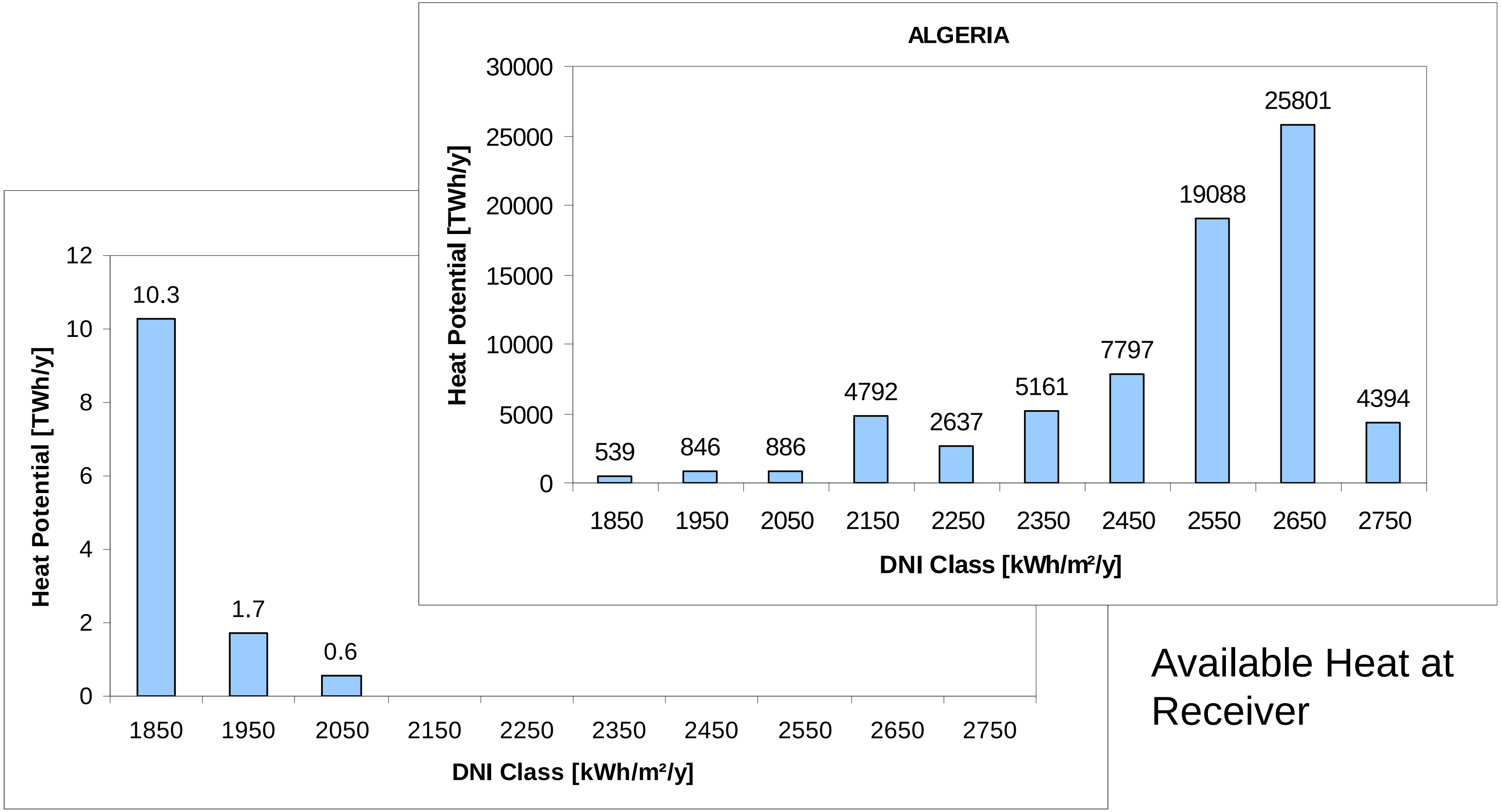
- 50 km Distance to Pipeline
- Acceptable DNI
- Available Land Area

Overlay of Data Sets for Italy



- 50 km Distance to Pipeline
- Acceptable DNI
- Available Land Area

Statistical Analysis

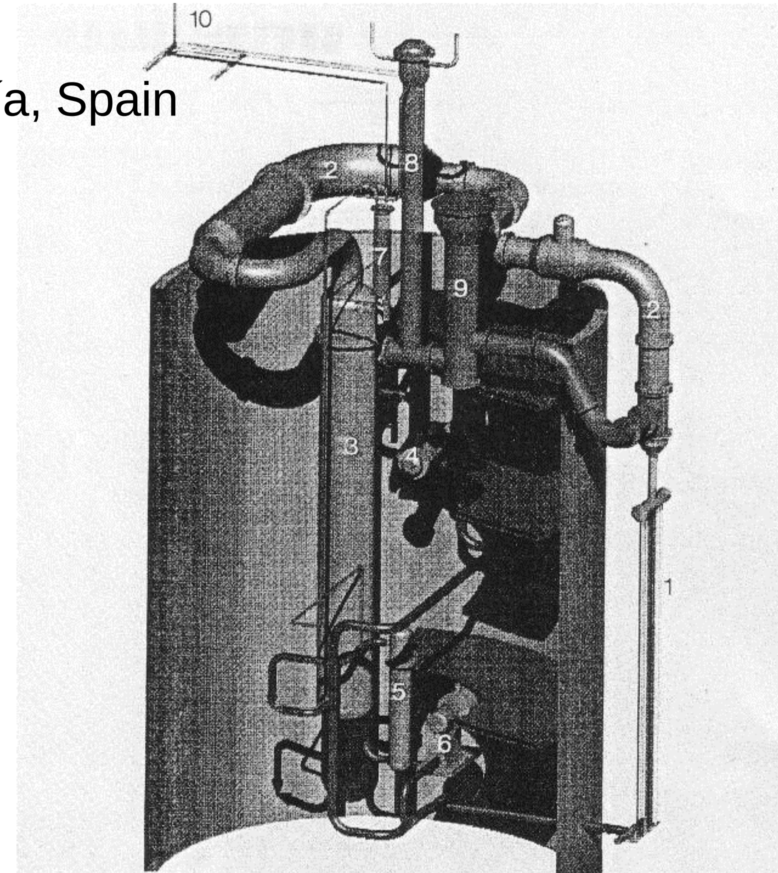


Available Heat at Receiver

ASTERIX: Allothermal Steam Reforming of Methan

- DLR, Steinmüller, CIEMAT
- 180 kW plant at the Plataforma Solar de Almería, Spain (1990)
- Convective heated tube cracker as reformer
- Tubular receiver for air heating

CESA-1, PSA, Spain. The solar radiation is collected by a field of heliostats and redirected to a tower, where different platforms allow the tests of various receiver technologies.



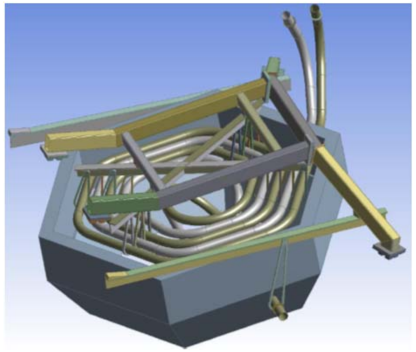
1 = Receiver, 2 = Heißgasleitungen, 3 = Rekuperator, 4 = Elektrischer Heizer, 5 = Kühler, 6 = Kompressor, 7 = Kühler E-106/7, 8 = Reformer V-101 mit Wärmeübertragern E-102/3/4, 9 = Elektrischer Heizer E-105, 10 = Fackel Z-102.

Near-term: Solar Production of Syngas (H_2 and CO)

Solar pilot plants demonstrated in the power range of 200-600 kW_{th}

Solar steam reforming of natural gas / methane

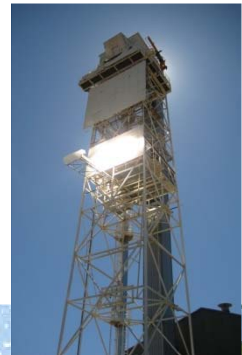
SOLGAS (200 + 600 kW_{th})
CSIRO, Australia



SOLREF (400 kW_{th})
DLR, WIS, Germany, Israel

Solar steam gasification of carbonaceous feedstock

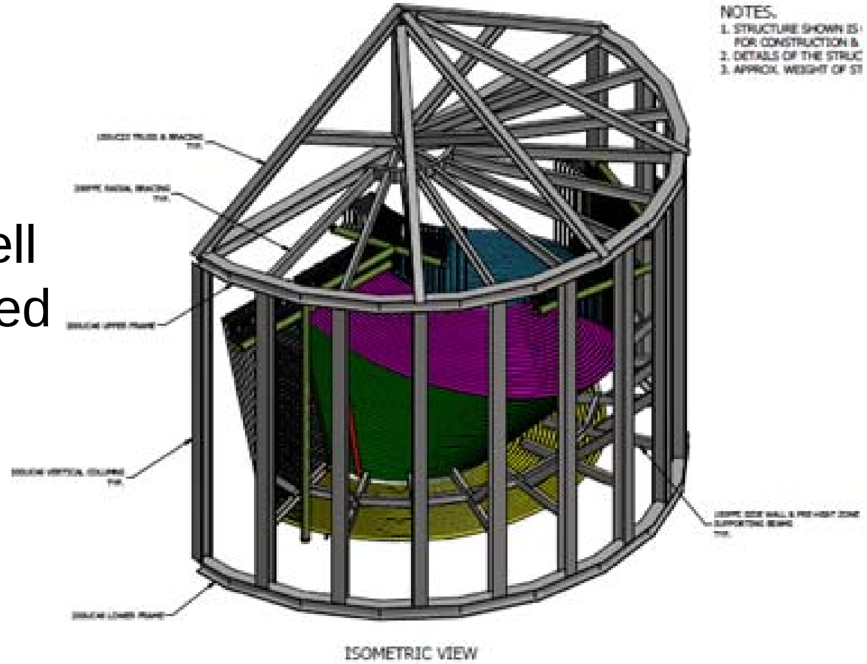
SYNPET (500 kW_{th})
CIEMAT, Spain



SOLSYN (250 KW_{th})
PSI, Switzerland

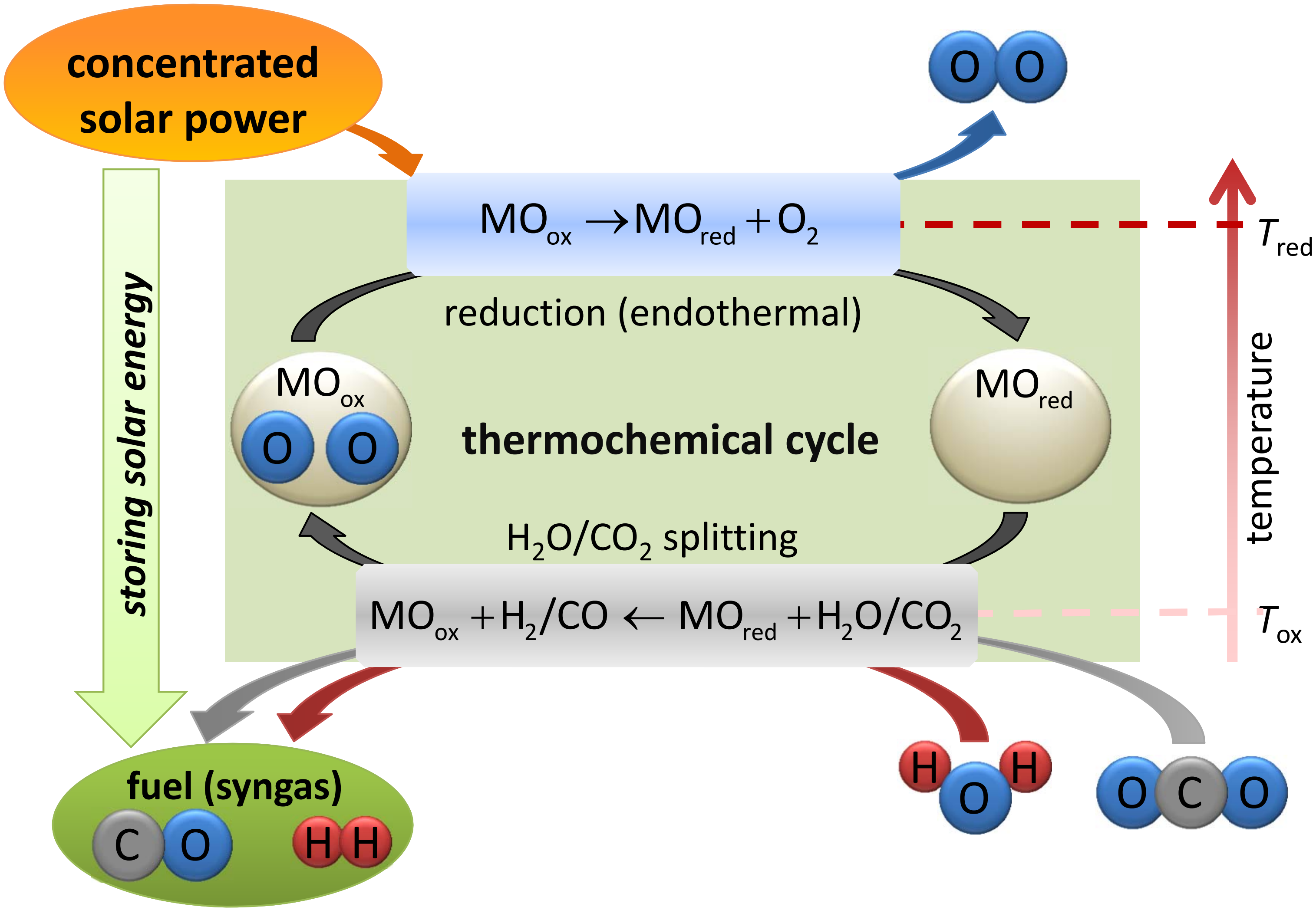
Scale-up of solar Natural Gas Reforming

- Australian Solar Fuels Program
- CSIRO develops industrial reformer
- 15 MW Demonstration at a natural gas well in the Western Australia Outback is planned



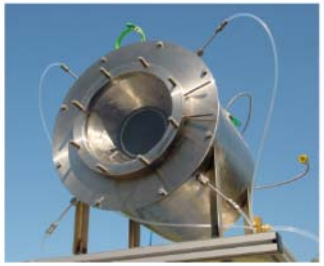
Robbie McNaughton, CSIRO, Australia

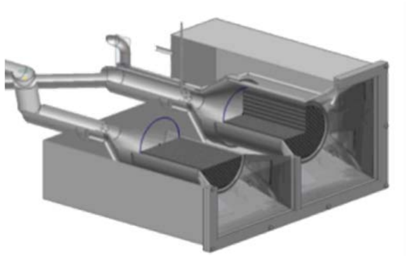
Thermochemical Cycles



HYDROSOL - An example for solar thermochemical water splitting (800 – 1200°C)

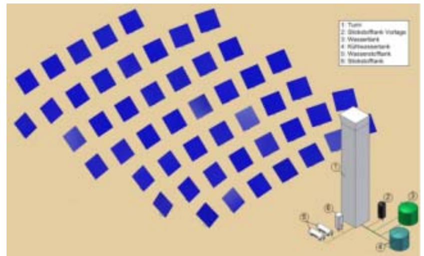
Hydrosol I
2002 – 2005
< 10 kW

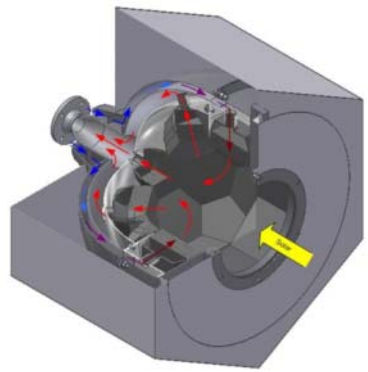




Hydrosol II
2006 – 2009
100 kW

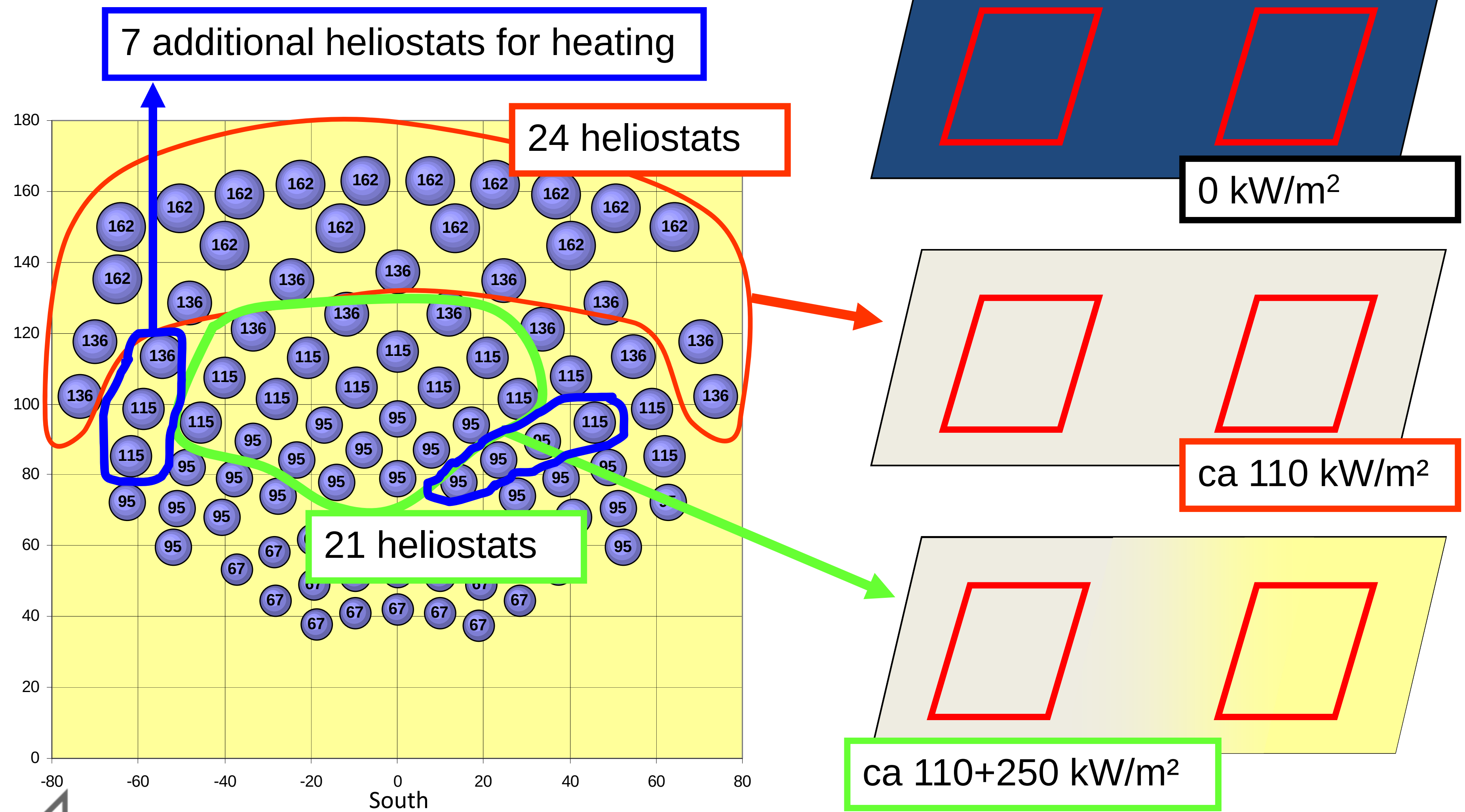
Hydrosol 3D
2010 – 2012
1 MW





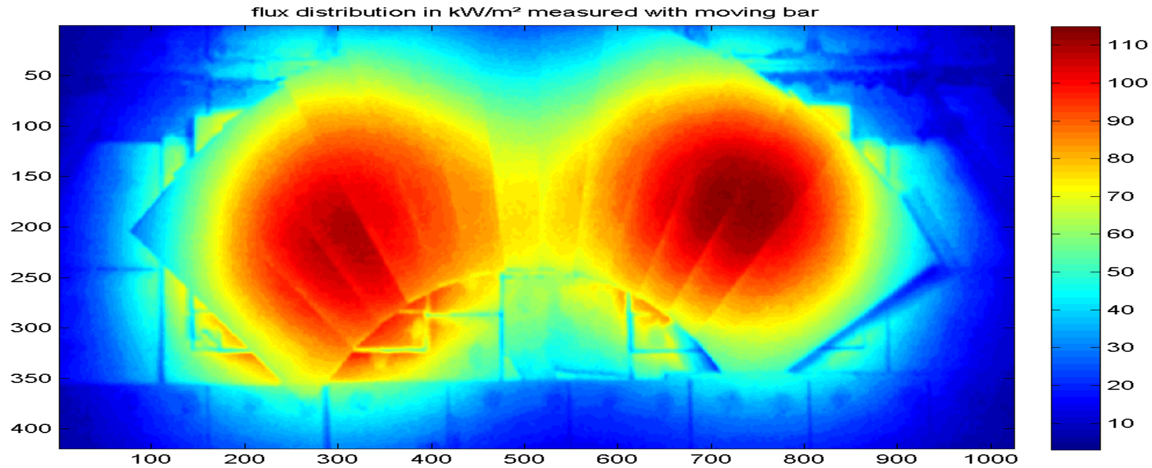
DLR

HYDROSOL II
Heliostat Operation

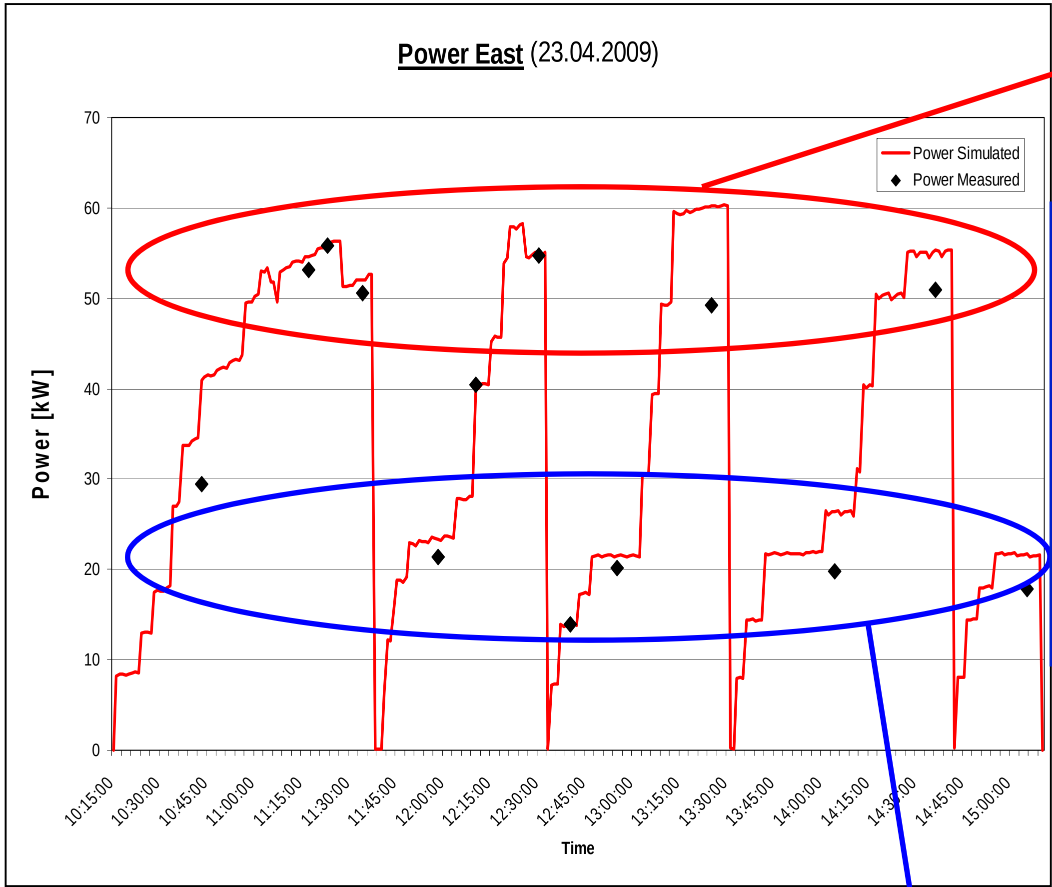


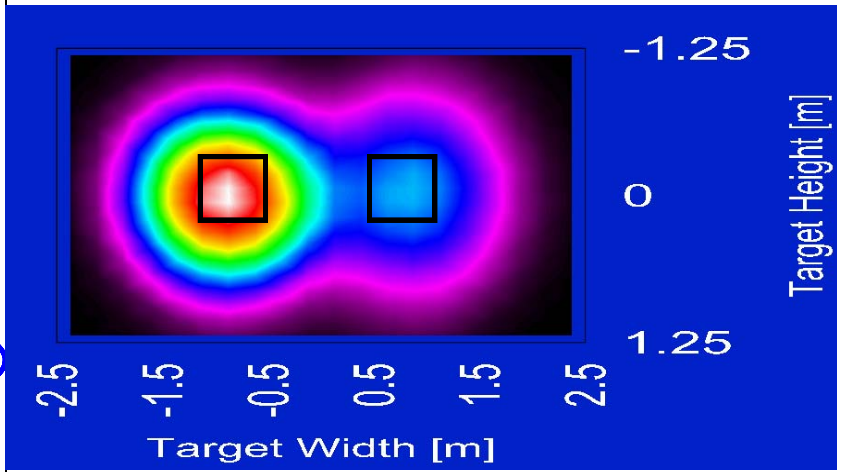
Hydrosol – Operation of Pilot Reactor

$Flux_{Max\,both\,Modules} = 115 kW/m^2$



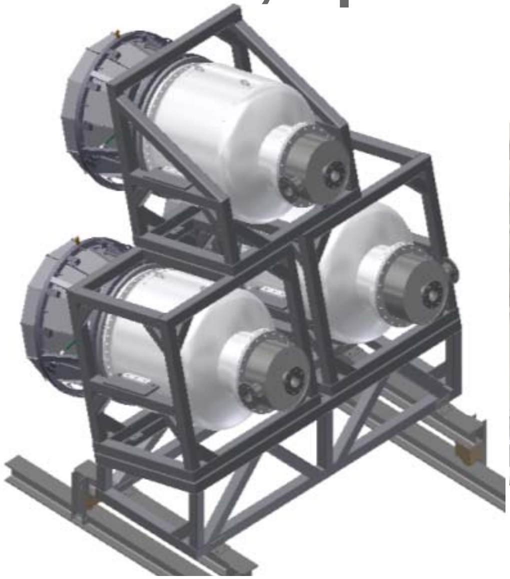
Modelling - Interface Heliostat Simulation Tool:





HYDROSOL Plant - CRS tower PSA, Spain

- European FCH-JU project
- Partner: APTL (GR), HELPE (GR), CIEMAT (ES), HYGEAR (NL)
- 750 kW_{th} demonstration of thermochemical water splitting
- Location: Plataforma Solar de Almería, Spain, 2017
- Reactor set-up on the CRS tower
- Storage tanks and PSA on the ground

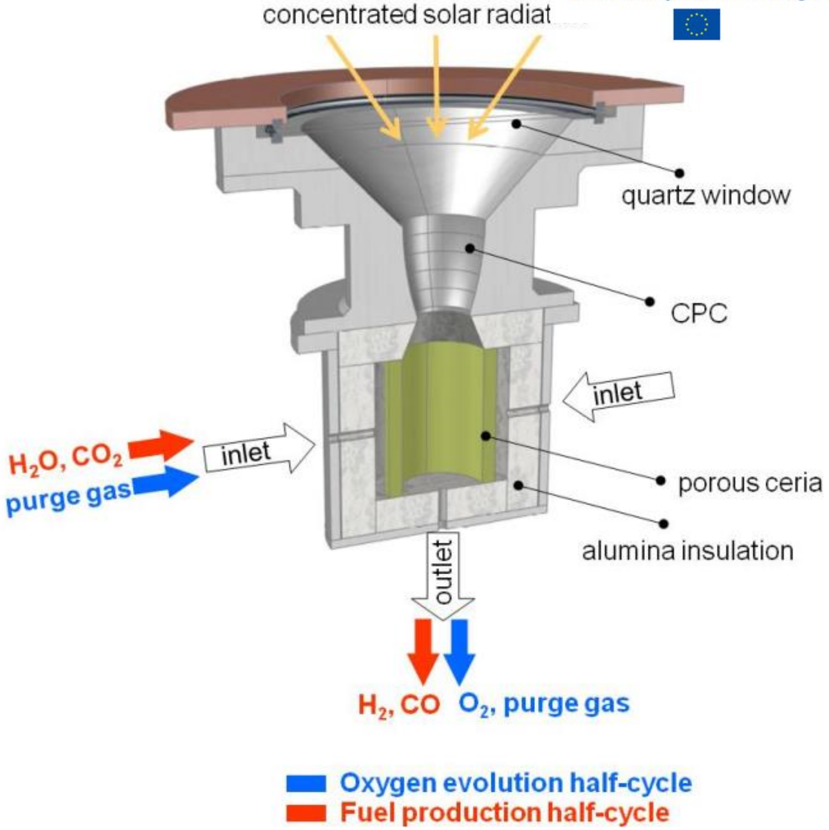


H_2O/CO_2-Splitting Thermochemical Cycles (800 – 1500°C)

Solar Production of Jet Fuel

- EU-FP7 Project SOLAR-JET (2011-2015)
- SOLAR-JET aims to ascertain the potential for producing jet fuel from concentrated sunlight, CO_2, and water.
- SOLAR-JET will optimize a two-step solar thermochemical cycle based on ceria redox reactions to produce synthesis gas (syngas) from CO_2 and water, achieving higher solar-to-fuel energy conversion efficiency over current bio and solar fuel processes.
- **First jet fuel produced in Fischer-Tropsch (FT) unit from solar-produced syngas**!

SOLAR-JET
Zero-carbon jet fuel from sunlight



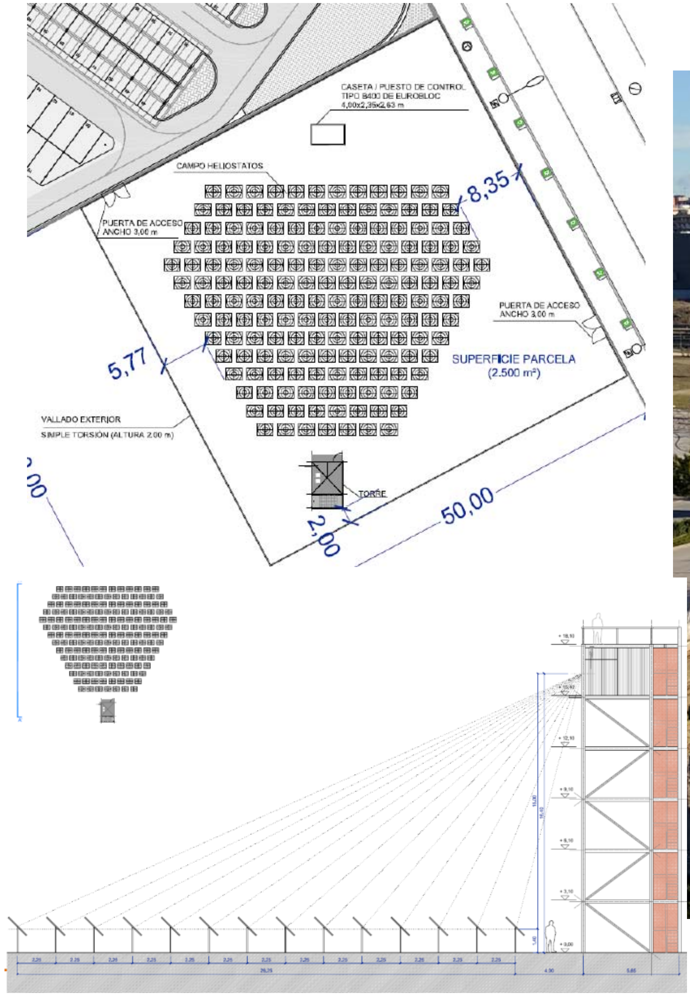
Int. J. Heat & Fluid Flow 29, 315-326, 2008.
Materials 5, 192-209, 2012.

Partners: Bauhaus Luftfahrt (D), ETH (CH), DLR (D), SHELL (NL), ARTTIC (F)
Funding: EC

http://www.solar-jet.aero/

DLR

EU - Sun-to-Liquid: Heliostat field and Tower, (IMDEA) Mostoles Madrid



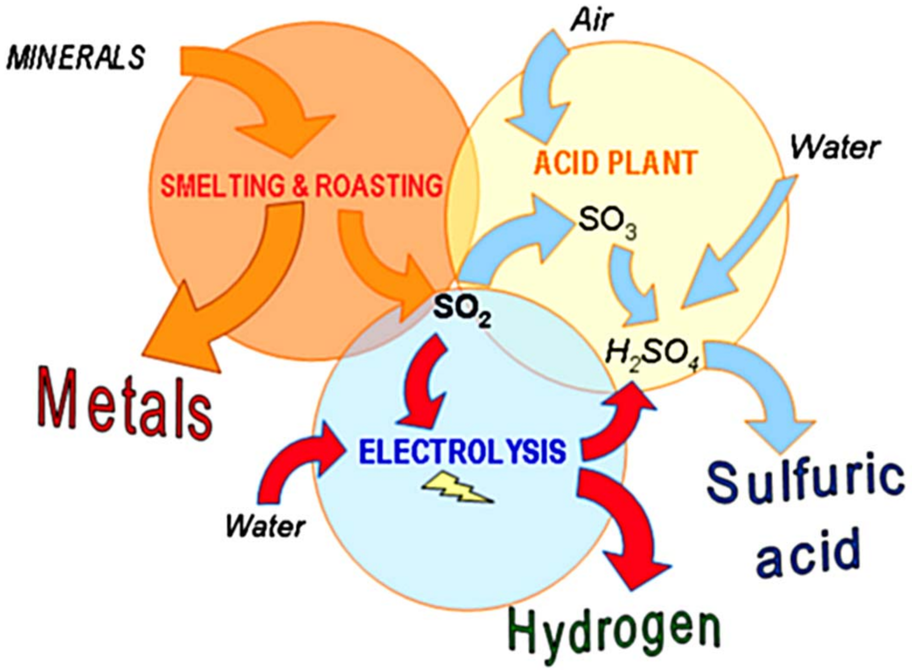
50kW Aperture (d=16cm); C_{mean}= 2500 (peak 3000); 169 concentrating heliostats;

SOL2HY2 – Solar To Hydrogen Hybrid Cycles

- FCH JU project on the solar driven Utilization of waste SO_2 from fossil sources for co-production of hydrogen and sulphuric acid
- Hybridization by usage of renewable energy for electrolysis
- Partners: EngineSoft (IT), Aalto University (FI), DLR (DE), ENEA (IT), Outotec (FI), Erbicol (CH), Oy Woikoski (FI)
- >100 kW demonstration plant on the solar tower in Jülich, Germany in 2015

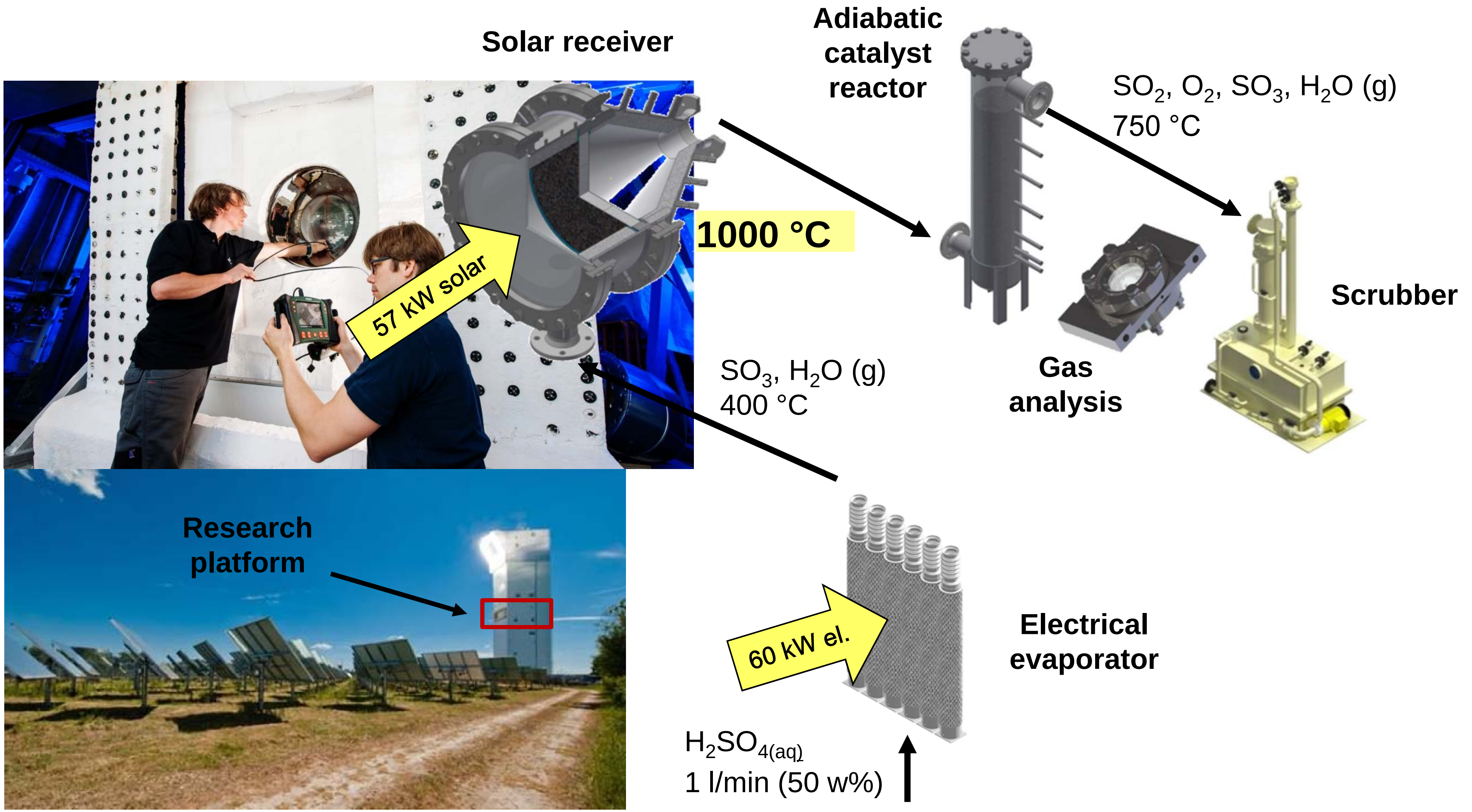
https://sol2hy2.eurocoord.com

Outotec™ Open Cycle (OOC)

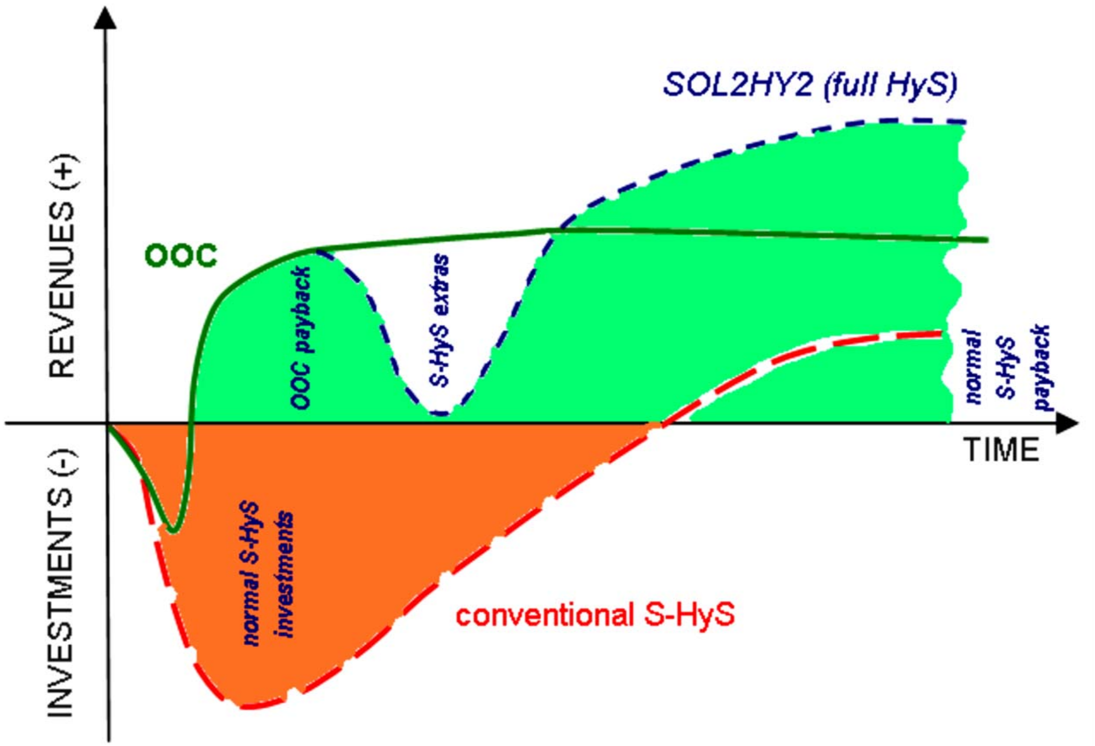


- Utilization of waste SO_2 from fossil sources
- Co-production of hydrogen and sulphuric acid
- Hybridization by renewable energy for electrolysis

Design of SOL2HY2 pilot plant



Investments vs. revenues



- Reduction of initial investments
- Financing of HyS development by payback of OOC
- Increase of total revenues

Thank you very much for your attention!